MSc Thesis
History and Philosophy of Science

Circularities in the empirical grounding of the cosmological principle

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After two tumultuous years, I have reached the end of this chapter of my life. Throughout this journey in the History and Philosophy of Science, I have grappled with many fascinating topics and rekindled a passion I once thought lost. Transitioning from physics to history and ending up in the philosophy of physics has been a unique, yet rewarding, odyssey, of my own making.

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Abstract

The standard model of cosmology is based on the cosmological principle, a metaphysical assumption employed because of its simplifying potential in modelling and purported success in matching observations. I critically examine the status and understanding of the cosmological principle as it is employed in cosmology, alongside its potential of being a testable hypothesis. I focus on some of the strategies employed by cosmologists to justify its use, to uncover if the reasoning is effective and if the evidence provided offers enough empirical support for the adoption of the principle, through the lens of the strongest current evidence in cosmology, the Cosmic Microwave Background (CMB). I show that, in the Planck mission, some data processing aspects create circularities, thus disallowing independent verification of isotropy, despite the many successful consistency checks. I also demonstrate that even with the isotropy of the CMB taken for granted it is difficult to independently show that homogeneity holds without additional assumptions or idealisations. More generally in cosmology, circularity threats are additionally caused by the issues of fitting, averaging, and idealising observations. Many of the concerns, however, are weakened with the understanding that cosmological models aim to describe the large scales of the observable universe and that the historical sciences, of which cosmology is one, place more weight on explanatory value over testing individual hypotheses. The secondary significance of testing does not mean that independently establishing the cosmological principle is not desirable, as it would still lead to significant epistemic gains. This understanding of cosmology supplements Adrian Currie's optimistic attitude towards the historical sciences through methodological omnivory — the idea that historical sciences take advantage of every available method to them —, in order to maximise epistemic gains and Hasok Chang's idea of progress being a primarily iterative process. I diverge from Currie in not arguing for ascribing the same epistemic standing to experimental and historical science practices in the quality of the epistemic goods they produce, as in the cosmological principle case, independent testing will put cosmology on more solid epistemic foundations.

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Chapter 1

Introduction

The cosmological principle is a key part of modern cosmology. It is an assumption that is present in the majority of conducted research, including in the ΛCDM model, better known as the standard model of cosmology. While there is no precise formulation of the cosmological principle used by all cosmologists, the general idea of the principle is quite clear. It claims that on large enough scales, the universe is homogeneous and isotropic, that is the universe has a uniform structure and looks the same in every direction. The version commonly employed applies these restrictions only to space and not time, and weaker formulations only make the claim statistically. In recent years, the validity of the cosmological principle has been called into question and brought to the forefront of debates within the cosmological community. While the principle is backed by evidence, as data collection became increasingly more precise, it has pointed to tensions between the principle and observations. This has caused physicists to reconsider the available evidence and propose tests for the principle.

One of the most widely used theoretical presuppositions in cosmology is that we live in a Friedman-Lemaître-Robertson-Walker (FLRW) universe, where space expands spherically. FLRW universes are built on a formulation of the cosmological principle, that is only valid throughout the spatial dimensions but not the temporal. Support for the cosmological principle comes both from the practice of cosmology, such as through data sets and interpretations based on modelling and simulations, and from specific considerations regarding the universe, for example, aesthetics. The principle was originally adopted prior to any empirical support due to its usefulness and aesthetic appeal, as the symmetries it implies greatly simplify the Einstein equations. This situation has historically almost enforced its use but has also been a driving factor for cosmologists to search for justifications for it.

From a philosophical perspective, this brings forth an interesting question, because while today supporting evidence has been brought forward, the embeddedness of the cosmological principle in the observation and interpretation of data might form a vicious circularity. When vicious circularities arise in hypothesis testing no genuine tests of its validity can ever be constructed as the assumptions guarantee the result (Elder, 2023). In science, we undoubtedly often construct tests based on theoretical presuppositions and use circular reasoning to explain the results. The theory-ladeness of observations is a well-established fact in the philosophy of science, however, that does not always mean that theories are impossible to test (Brown, 1993). It becomes an issue when the experimental apparatus depends on some level of its operation on the theory under consideration (Franklin et al., 1989). Proper calibration with independent equipment can mitigate the issue, as can ensuring that the apparatus is behaving sufficiently differently from the tested phenomena, and as such would not hide any discrepancies (Franklin et al., 1989).

These concerns are amplified in the historical sciences because confirmation holism is an ever-present threat. Holism in the philosophy of science is the idea that hypotheses cannot be tested in isolation as they are always embedded in a broader web of theories and assumptions, a problem known as the Duhem-Quine thesis (Duhem, 1954; Quine, 1951). While holism is a concern generally in science, the methodology of the historical sciences makes isolating hypotheses even more difficult. Historical sciences are not a unified field, but a disparate collection of disciplines that share certain features, principally that they make claims about objects in the past from the traces observed today (Currie, 2018). Methodologically historical sciences have been contrasted with the exemplary scientific practice of experimentation, which has the ability to falsify hypotheses (e.g. Hacking, 1989). The lack of experimental practices can make the historical sciences appear epistemically deficient. This is because they amplify the concerns of holism by lacking the ability of traditional experiments to manipulate the entities involved, resulting in models with interrelated hypotheses that cannot be independently tested. Several authors, however, have responded to these claims, analysing the methodology of the historical sciences and arguing why it can be on par with experimental science (Cleland, 2002; Forber, 2011; Currie, 2018).

Cosmology is a historical science as it primarily relies on observations from our past light cone to reconstruct the evolution of the universe and make claims about those past entities. As a historical science, several characteristics of cosmology suggest that the cosmological principle might be problematic. The issue of holism is generally tied to circularities in the historical sciences since the principle under scrutiny is never the only assumption in a model and thus its falsification, in isolation, becomes a difficult task. The threats of circularity and holism are amplified by the fact that much of the current understanding of how astronomical entities behave is model-dependent, because of the difficulty of studying entities in the full general relativistic context without any simplifying assumptions (Anderl, 2016). Additionally, in astronomical observations, there is no way to manipulate the entities being studied as astronomers can only observe the past light cone, further limiting the data that can be gathered and the tests that can be conducted (Anderl, 2016). Lastly, what differentiates cosmology from other historical sciences, is the uniqueness of the universe as a physical object of study, as this presents conceptual challenges when one tries to validate it (Ellis, 2007). All these amplify concerns, as they reduce the number of tests and independent observations astronomers can conduct.

Despite the conceptual hurdles, cosmologists have constructed several consistency tests for the cosmological principle and other tests that constrain or rule out alternative models. An examination of these tests is necessary from a philosophical perspective to establish if with precise enough data, these tests can be seen as genuinely confirming the principle, or if the underlying assumptions are guaranteeing the results. Beyond the tests, it is also significant to understand how modelling works in cosmology and what the available methods of inquiry are, as these can decrease the impact of the circularities. The way cosmology makes progress is a key notion in differentiating both the status and the effects of circularities on the discipline.

Standard accounts of progress generally tied it to approaching truth or truthlikeness in a linear evolution. Karl Popper (1959) emphasises the advancement of knowledge through the corroboration of certain hypotheses and the falsification of the rest. Imre Lakatos (1970) and Larry Laudan (1978) characterise progress respectively through the ability to make novel predictions within a research program and through the refinement and improvement of problem-solving techniques within a particular research tradition. Philosophers of the historical sciences, on the other hand, tend to emphasise the messier, indirect, and pluralistic character of progress (Currie, 2018). Pragmatist approaches adopt a similar tone, such as Hasok Chang (2022), who writes of iterative progress according to the aims and methodologies of each discipline. These latter approaches provide a much more substantive way to understand cosmology and they are utilised to show that cosmology is making progress even in the presence of circularities.

Philosophical work on the cosmological principle has largely focused on clarifying what the principle means and its application beyond the observable universe. Claus Beisbart and Tobias Jung have attempted to analyse the principle and explicate its differences from the Copernican principle, which other authors appear to have occasionally confused (Beisbart & Jung, 2006). Beisbart (2009) has also discussed the potential of the principle to break empirical underdetermination of cosmological models, concluding that if not assumed a priori, it is impossible to substantiate beyond the observable universe. The underdetermination issue has been highlighted by Jeremy Butterfield (2014), as well, and he has explored several ways to answer it, including the cosmological principle, but he finds none of them satisfying. Other authors more recently have even suggested that assuming the cosmological principle does not on its own break model underdetermination in cosmology (Ryan, 2024). Minimal work has been done regarding the validity of the evidence offered for the principle in the observable universe, and it has been done primarily within the physics community.[1] This project aims to begin filling this gap in the literature to examine whether some of the most important evidence for the cosmological principle suffers from a theory-ladeness that transforms into vicious circularities and if the principle is untestable because of holism, while contributing to the larger philosophical literature on the epistemology and methodologies of cosmology.

The use of principles in physics has a long history. Recent philosophical work on the role of principles in physics was conducted by Enno Fischer (Forthcoming), who divided principles into principles of nature, principles of epistemic action, and guiding principles, which combine aspects from the other two. Principles of epistemic action are methodological choices that guide epistemic inquiry, such as Occam's razor. Principles of nature make claims about the properties of the object of study and have been used as the starting point for deriving theories historically. The popular success story that is usually cited in circles discussing the importance of principles is Albert Einstein's use of

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[1] A review of these efforts has recently been published by Aluri et al. (2023).

the principle of relativity and the light postulate to derive special relativity, and the addition of the principle of equivalence to formulate general relativity.[2] Lastly, guiding principles partly fulfil both a descriptive role and a guiding role, by being less well-defined and not necessarily empirically supported, one example of which is the naturalness principle. The cosmological principle, in the first half of the twentieth century, was considered a principle of nature, based partly on observations, and as such set constraints on what was physically possible in the already-established theory of general relativity. Throughout its history, it has gradually transformed into a guiding principle with increasingly weaker formulations that define the domains of interest. In modern cosmology, while it is recognised that the principle is not a necessary part of nature, attempts concentrate on backing it with observations that will prove its validity.

In this project, I analyse the strategies used by cosmologists to support the principle on empirical grounds and uncover if they are viciously circular and as such do not give a genuine basis for the cosmological principle. Additionally, I examine the effect of these circularities on the practice of cosmology. The case study of the project is the Cosmic Microwave Background (CMB) and the purported evidence that is derived from it, as it is considered one of the most well-understood phenomena in the history of the universe. It is supplemented with an investigation into the general practices in cosmology, specifically the dialogue between observational data, simulations, and modelling, through the lens of making progress. I argue that there is a genuine threat of vicious circularities because of holism, which makes independently testing hypotheses about cosmological models difficult, but that cosmology is capable of making progress in other ways. Progress in cosmology can be understood as a primarily iterative process, as defined by Hasok Chang (2022), which is achieved by improving model constraints, changing aspects of the standard model in light of new evidence, and so forth, but also as a process of eliminating alternatives and suggesting new physics. Moreover, the circularities are not as concerning as in the experimental sciences because historical sciences value explanatory power over falsifying individual hypotheses. The lesser significance of testing does not mean that independently establishing the cosmological principle is not desirable, as it would still lead to significant epistemic gains and be another form of progress. This understanding of cosmology supplements the optimistic attitude of Adrian Currie (2018) towards the historical sciences, as they can make progress, supplemented by "methodological omnivory", the idea that historical sciences take advantage of every available method to them, in order to maximise epistemic gains. I diverge from Currie in not arguing for ascribing the same epistemic standing to experimental and historical science practices, since as I show in the case of the cosmological principle, independent testing will put cosmology on more solid epistemic foundations.

In order to demonstrate this argument, I first introduce the cosmological principle. I review how it is employed in cosmology and track its history in the field, to showcase its embeddedness (§2.1). Subsequently, I present the physics and mathematics of the principle, to demonstrate the way it simplifies the equations and lay the groundwork for future chapters (§2.2). In order to deliberate on whether the principle is supported well, an examination of the ways its adoption is justified is required, within the context of the struggles present

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[2] The counterexample to this story is quantum mechanics.

in observational cosmology (§2.3). The cosmological principle is often supported using another principle, the Copernican principle, thus I shortly discuss that principle, as well, and the grounds for its justifications (§2.4).

The second part of this project is concerned with investigating the way the CMB is understood and how it is utilised as an argument for the validity of the cosmological principle. It is important to understand the underlying assumptions that go into interpreting the CMB. For this, I focus on the latest observational data of the CMB gathered by the Planck Collaboration and released in papers spanning from 2014 to 2020. I first offer an introduction to the CMB and an analysis of how the isotropy of the CMB is justified (§3.1, §3.2). I examine closely the data pipeline of the Planck mission — with a particular focus on the calibration using the dipole and the component separation using simulations—, how the isotropy is derived, and the consistency tests performed by the Planck team (§3.3). I show that despite the success of the tests there still exist some concerns regarding the verification of the isotropy of the CMB. Then, assuming the isotropy of the CMB I look into the strategies for arriving at the cosmological principle, primarily through the generalised EGS theorem and the Copernican principle, and explicate their issues (§3.4). Lastly, I analyse the various tests that can be constructed with the CMB for consistency on FLRW models and to place constraints on alternative models (§3.5). I review the assumptions that underlie both the tests and the reasoning cosmologists utilise and show that they do not result in vicious circularities but I argue that the tests have limited applicability without additional assumptions and idealisations. While testing some other categories of models has largely been a success, tackling the problem of direct and independent verification of the FLRW geometry through the CMB requires unrealistic idealisations for current cosmology.

Lastly, I examine the scope and limitations of our knowledge in cosmology through the general issues in cosmology and how the methodology and goals of the discipline address these challenges to make scientific progress. Specifically, I begin by looking into the way averaging, fitting, and idealising observations create further circularities in cosmology (§4.1, §4.2). These practices of cosmology which attempt to match observations with theoretical models are limited by the nonlinear nature of general relativity and the nature of the available observations. Subsequently, cosmology is examined through the lens of its aims and the methodology of the historical sciences, making explicit the challenges the discipline faces (§4.3). I argue that these show that for cosmological models the threat of circularities diminishes, in comparison with the experimental sciences, as independent testing is a secondary concern over explanatory value, though it can still play an important role. I finish by demonstrating that despite the implications of the multifaceted issues in the field and the threats of circularity, cosmology is thriving and making gradual progress (§4.4). Progress can be achieved (i) iteratively through tests, constraints, new methods and so forth (ii) eliminatively through the discarding of alternative models, and (iii) through both with the suggestion of new fruitful paths in physics. Cosmologists are aware of the problems and are continuously attempting to solve them, with improvements in methodology, theory, and technology, which can eventually even lead to independent tests of the cosmological principle. While the threats of circularity from the principle are lessened by the methodology, the epistemic gains from achieving independent testing are still significant. The cosmological principle has served cosmology well until now as a valuable guiding principle. For further progress to occur and to potentially reestablish it as a principle of nature, it is vital to continue testing and constraining it but to also consider alternative models.

Chapter 2

The Cosmological Principle

2.1 Definitions and History

The cosmological principle is the assertion that the universe on sufficiently large scales is homogeneous and isotropic. It is important to clarify what these terms mean because they have precise mathematical meanings. Isotropy describes the uniformity of a property under consideration on all orientations, or no matter the direction the said property remains unchanged. Homogeneity generally refers to a property being spread out uniformly or being consistent from point to point. In cosmology, isotropy and homogeneity are connected specifically with observations that can be made from positions within spacetime. Isotropy can thus be restated as the idea that all observations around a point are the same irrespective of the direction that the observer chooses to turn to (Beisbart & Jung, 2006). Homogeneity, on the other hand, means that any two observers in two different positions in spacetime would be unable to distinguish their position based on their observations since they would be identical (Beisbart & Jung, 2006). From these, one can discern that there is a translation symmetry implied by homogeneity and a rotational symmetry indicated by isotropy. Since the principle is concerned with observations, it is commonly employed by cosmologists as a restriction to the distribution of matter in the universe, as detected signals are generally from matter-like sources.[1] In modern FLRW models, such as ΛCDM, the even distribution is extended as a requirement to dark matter and dark energy, even though neither can be observed directly and their exact nature remains a mystery. Homogeneity, therefore, conveys the idea that matter is distributed uniformly throughout all of spacetime and isotropy that the matter distribution appears the same, regardless of the direction one looks from our vantage point.

From figure 2.1, one can see that homogeneity and isotropy do not necessarily demand one another. A vector field, such as the electromagnetic field, could be spread out uniformly throughout spacetime, with consistent intensity and directionality, making it impossible to discern a difference in position by measuring it. In every position, however, observing the field is not isotropic, because of its directionality. The isotropic depiction, instead showcases how from a central point one could view an inhomogeneous distribution as

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[1] Gravitational waves are a signal that in general is not considered matter-like but astronomers can only detect major gravitational wave signals which arrive from singular major events, so they are not usually considered in discussions about the general homogeneity and isotropy of the universe.

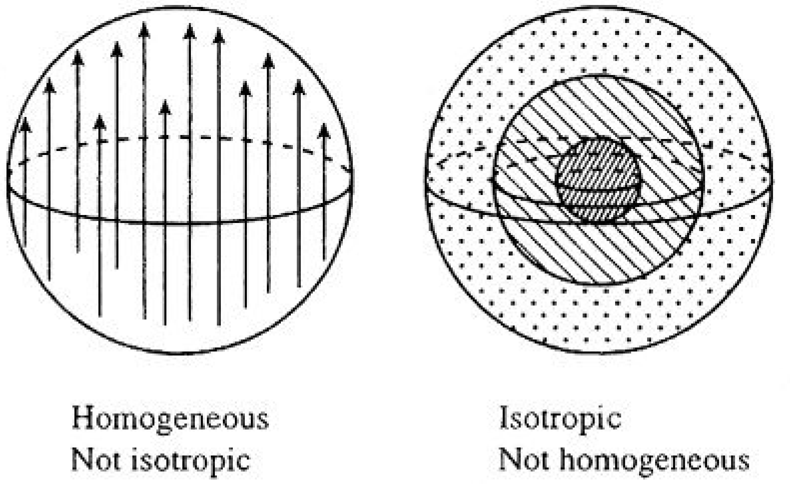

Figure 2.1: Isotropy and Homogeneity. Figure taken from James Schombert's lectures on cosmology.

spherically isotropic, something not possible from any other point. Connections between the two concepts exist, specifically that isotropy around one point and homogeneity mean that there is isotropy around every point. The converse holds, as well, which translates to isotropy around every point implying homogeneity.

The idea of the cosmological principle has a long history within cosmology. In terms of its application, it was an underlying assumption in much of the early work in modern cosmology, a field that only began to be rigorously scientific following the publication of Albert Einstein's general relativity. The first solutions of the field equations for the universe suggested by Einstein (1917) and subsequently by Willem de Sitter (1917) assumed the principle in a closed and static universe, which translates to spacetime being finite and unchanging, in the latter part of the 1910s (Kragh, 2007). In the following decade, Alexander Friedmann (1922) would give the first cosmological solutions of a dynamic nature allowing for the general expansion of spacetime, with Georges Lemaître (1927) also recreating the result (Realdi, 2019). The expansion of the universe would become a known fact by the 1930s, validating these dynamical solutions. During those years, however, the first calculations for inhomogeneous models were done by Lemaître (1933) and Richard Tolman (1934), who for the first time questioned whether homogeneity is something found throughout the universe (Kragh, 2007). Tolman recognised that the homogeneous models did not precisely match the data and nothing demanded that the whole of the universe would be homogeneous even if the observable part we inhabit is (Tolman, 1934). This was the beginning of isotropic and inhomogeneous models, using the inhomogeneous distribution of matter to explain the expansion of the universe. These types of models would remain unpopular for the foreseeable future.

While in the first few decades of its existence modern cosmology had implicitly supposed the principle it made no efforts to explicitly spell it out. This changed with Edward Arthur Milne who first formulated the principle as a postulate expressing Einstein's idea that two observers moving uniformly would make the same observations. Milne not only clearly laid out the presupposition but considered it a fundamental principle of nature from which he could deduce an alternative theory to general relativity and another way to get viable cosmological models (Milne, 1935). This formulation of the principle is concerned purely with the three spatial dimensions and as such demands only spatially that the universe is homogeneous and isotropic. This translates to the conditions of the principle holding for foliations of spacetime, or for the universe being homogeneous and isotropic within different snapshots in time. The change in the temporal dimension is today generally taken to be the uniform accelerating expansion of space, despite Milne disliking that idea. While Milne's approach did not gain widespread recognition it did inspire Howard Robertson (1929) and Arthur Walker (1935) to make mathematically explicitly what the principle was suggesting for covariantly moving observers, deriving the now famous Robertson-Walker metric, that characterises a uniformly spatially expanding spacetime (Urani & Gale, 1993).

By the end of the 1940s interest in the principle was renewed with the invention of steady-state models and the Big Bang models gaining momentum. By that time it was well established observationally that the universe was expanding. Hermann Bondi, Thomas Gold, and Fred Hoyle wanted to create a model that adhered to observations but extended Milne's cosmological principle to include a temporal translation symmetry. They named it the perfect cosmological principle, which stated that the universe is homogeneous and isotropic throughout all of spacetime. (Bondi & Gold, 1948). For this model to correspond with the observations of expansion and maintain homogeneity, its creators envisioned an eternally expanding universe where matter is continually created to maintain homogeneity (Kragh, 2019). This evidently violated the principle of energy conservation thought to be a cornerstone of physics, but it was a compromise steady-state advocates were ready to make to elevate the cosmological principle to hold throughout spacetime and avoid certain issues, such as the beginning of time. The models have fallen out of favour, with the discoveries of the cosmic microwave background and quasars in the 1960s, which pointed towards the universe being considerably different in the past (Kragh, 2019).

Throughout the first few decades of cosmology, the cosmological principle played a vital role. Both by being an unspoken assumption and after it was explicitly stated, it appeared to be unavoidable in the search for workable solutions to the Einstein equations. Limited observational capabilities restricted the potential of what data could confirm, though some observations did line up with what was expected from a homogeneous universe (Peebles, 2020). Despite that, the expansion of the universe was firmly established and many observations fitted with FLRW models, suggesting an origin point in time known as the Big Bang.

The 1960s and 1970s saw another major development, in the introduction of matter fluctuations to explain structure formation in the universe (Longair, 2019). The absolute spatial homogeneity of the FLRW models was not sufficient to explain how the universe evolved and how matter clumped together to create structures, such as galaxies. For this, perturbations of the models started to be considered, as a way to match empirical observations. Thus, the principle was weakened further to only hold statistically, or for a universe that is almost homogeneous and almost isotropic. Even within our local neighbourhood in the observable universe, there is sufficient variation in the distribution of matter, which coupled with the difficulty of defining the scale on which the uniformity is supposed to be

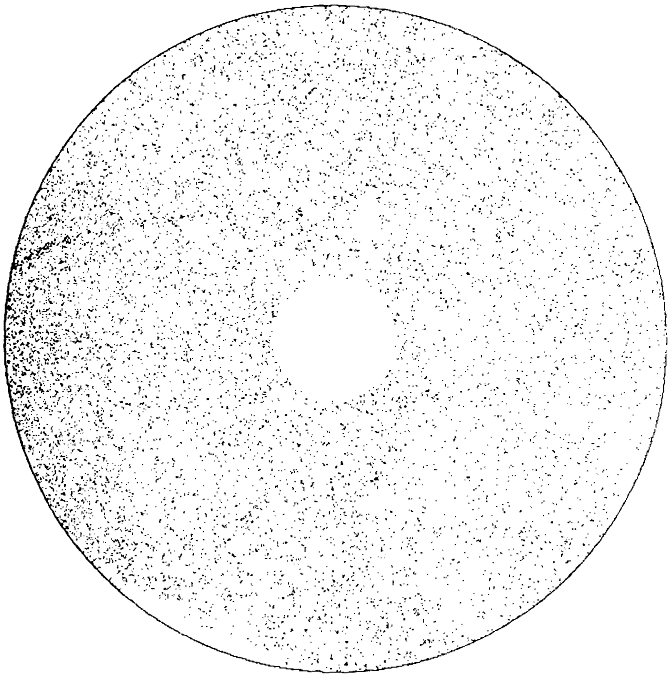

Figure 2.2: Angular distribution of brightest radio sources. Figure taken from Peebles (1993), created based on the catalogue of Gregory & Condon (1991).

observed, makes it easier to adopt the principle on the grounds that the homogeneity and isotropy hold for small perturbations and over sufficient averaging on large scales, a notion I will return to in §4.1.1.

2.2 The Physics of the Cosmological Principle

In general relativity, spacetime is related to matter through the Einstein field equations.[2][3]

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G T_{\mu\nu} \tag{2.1}$$

Because of certain symmetric properties of the Einstein equations, there are only ten nonlinear independent equations, that need to be solved in order to fully define the metric at a certain point. The equations are considered incredibly difficult to solve without simplifying assumptions. This is because the independence of the equations translates to a large number of tensor components that define the geometry that cannot be determined easily. Simultaneously, the equations are nonlinear, a fact that arises from the curvature of spacetime affecting the distribution of mass and energy, which in turn affects the curvature itself, making it difficult to find exact analytical solutions. Instead, what physicists do is make simplifying assumptions by adding certain symmetries to the metric $g_{\mu\nu}$, reducing the number of independent tensor components. One of the most common simplifying procedures is assuming the cosmological principle. The principle defines a family of models called

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[2] For now I will ignore the contribution of the cosmological constant.

[3] This analysis follows Carroll (2019).

the Friedman-Lemaître-Robertson-Walker (FLRW) models, which are exact solutions to Einstein's equations. The metric of FLRW models is

$$ds^2 = -dt^2 + a(t)^2 \left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \right] \tag{2.2}$$

As is evident from the metric there is a separation of space and time as necessitated by the formulation of the cosmological principle. FLRW manifolds consist of $\mathbf{R} \times \Sigma$, where $\mathbf{R}$ represents the direction of time and Σ is a three-dimensional maximally symmetric space representing the spatial dimensions, meaning Σ has the maximum number of symmetries that space could have. This includes spatial translation and rotation symmetries which are implied by spatial homogeneity and isotropy respectively. The scale factor $a(t)$ defines how rapidly the universe is expanding or contracting while the terms to its right define the three-dimensional spherical change. In each time slice the curvature and metric remain constant throughout the manifold.

In order to derive useful equations some assumptions about the form of matter need to be made. In cosmology, matter is often represented as a perfect fluid. Perfect fluids are an idealised form of fluid that can be completely characterised by their energy density ρ and their pressure p, which is isotropic in their rest frame. These quantities are only such for observers in the rest frame of the fluid, or comoving with it. In a spherically expanding universe, if an observer views the distribution of matter as a perfect fluid then the matter needs to, at the very least, be isotropic around the observer, for the energy density and pressure need to be constant and isotropic (Ellis et al., 2012). If all comoving observers view it as a perfect fluid then the distribution of matter is homogeneous and characterised by an FLRW metric. For a comoving observer the velocity four-vector U^μ is given by

$$U^\mu = (1, 0, 0, 0) \tag{2.3}$$

and the stress-energy tensor of the fluid is

$$T_{\mu\nu} = (\rho + p)U_\mu U_\nu + p g_{\mu\nu} \tag{2.4}$$

By substituting the relevant tensors in the Einstein field equations (2.1) the ten independent equations are reduced to two relatively simple differential equations, known as the Friedmann equations, where the variable under consideration is the scale factor $a(t)$.

$$(\frac{\dot{a}(t)}{a(t)})^2 = \frac{8\pi G}{3}\rho - \frac{k}{a(t)^2} \tag{2.5}$$

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3}(\rho + 3p) \tag{2.6}$$

These equations also define a preferred rest frame, which is the one comoving with the expansion of the universe, as it would be the only one which would be observing the isotropy. Because of the covariance of general relativity, there are no preferred foliations of spacetime, as the theory remains invariant under coordinate transformations, removing the concept of a preferred rest frame as known in Newtonian physics. The frame defined by the Friedmann equations is preferred in the sense that the Einstein equations are easier to solve, because of the way we defined the velocity. A rest frame such as this is also global, meaning all observers from any spacetime point in the universe can see it. This creates a reference point that allows us from our unique spacetime position to make inferences about what other observers are seeing in other parts of the universe.

While the Friedman equations simplify equations (2.1), they do not solve the problem of nonlinearity directly, because the scale factor $a(t)$ and its derivative are raised to the power of two and because the energy density ρ generally depends on $a(t)$. Nevertheless, solving these two equations based on astronomical observations is significantly easier than dealing with the whole of equations (2.1). At different eras of the universe when different components of the energy stress tensor dominate the other contributions, the equations can become linear.

2.3 Issues with Justifying the Cosmological Principle

Historically the principle was adopted a priori and considered applicable to the whole universe. Simply accepting the cosmological principle beyond our observable universe is difficult to justify as several authors have argued (Beisbart, 2009; Butterfield, 2014). While some scholars claim that the aim of cosmology is to understand the totality of the universe, such an aim seems unrealistic and not reflective of the practice, something that is further discussed in §4.3.1. A major limitation to determining the global properties of the universe is that general relativity is an inherently local theory. It allows us to characterise the behaviour of matter and spacetime in certain neighbourhoods, which in principle could significantly vary from each other. When this is coupled with the belief that the observable universe appears to be substantially smaller than the actual universe, it makes any grandiose assumptions about the global nature of spacetime difficult to substantiate. It has been shown that the global structure of spacetime will always be observationally underdetermined, which means that the evidence from our observable universe will necessarily be insufficient to conclusively determine the global structure of spacetime (Manchak, 2009).[4] This happens because "sister" structures of a spacetime can exist, where locally they match our observations, while globally they have different properties. There are ways around this if, for example, one expects a physical process to create a uniform global structure, such as setting up homogeneous initial conditions or global inflation, which smooths out the distribution of matter. Undoubtedly, though, if one takes a priori the principle to hold this allows for solutions to general relativity that have a global character. If all observers in spacetime view a homogeneous and isotropic universe they will solve the Einstein equations the same way, because the (FLRW) metric they will be using will be the same.

Since adopting the principle has a multitude of physical merits, as discussed in §2.2, cosmologists have been increasingly searching for empirical backing to justify their use of it. One of the two horns of the principle, isotropy around our position, appears to have a fairly straightforward way of being established. Why do we not just turn our detectors to

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[4] This is valid provided that general relativity holds throughout the universe. In principle, there is nothing that restricts physics from being completely different outside our observable universe, and as such lead to a very different universe than the one expected.

the skies and observe the distribution of matter around us? By reconstructing our past light cone we could conceivably check whether isotropy is present. While it sounds simple, such an endeavour is not without its hurdles.

Cosmologists have considered this with idealised observations, which means that all observational quantities are known accurately. In such a scenario, with only demonstrating that four observables are isotropic — angular diameter distances, number counts, bulk velocities, and lensing — one can infer that the metric of the observer is also isotropic (Ellis et al., 1985). This result can be extended to include dark energy (Clarkson & Maartens, 2010). As a matter of fact, it has been shown that one can go beyond this on a purely observational basis through the Observational Cosmology Theorem. The theorem states that the data available in our past light cone should be sufficient to not only determine isotropy but the general spacetime geometry, as well (Ellis et al., 1985).

This is, unfortunately, practically impossible to carry out. Certain idealisations are always necessary for conducting observations in cosmology, especially since we do not have direct access to the object of investigation. Astronomers can track the radiation signals emitted from the sources and use those observables to determine whether there is isotropy in our past light cone. The signals arrive from the sky, a 2-dimensional sphere surrounding the spacetime region that the Earth occupies, by intersecting our past light cone as shown in figure 2.3. Extrapolating these data to create a 3-dimensional picture is not trivial and is one of the major issues in cosmology (Ellis, 2007). Ideally, cosmologists want to foliate based on a chosen rest frame, to different snapshots of the past, for which to test homogeneity. Recreating the actual distribution though, requires precise measurements of the distances between objects. Ascertaining the distances of objects requires either the use of standard candles, which have limited applicability, or defining a model of the spacetime evolution that defines how radiation propagates (Ellis, 2007), issues that are expanded upon in §4.2. The usual model adopted is FLRW, which is a model that assumes the principle we would like to generate empirical evidence for, creating a circularity.

Relying on observations from the past light cone is both a boon and a problem within cosmology and is what makes it a historical science, something that will be discussed further in §4.3.2. On the one hand, signals arriving from different points in the universe can give vital information about its earlier history. On the other, besides the issue of determining distance, because all evidence arrives from our past light cone, we are very limited in the evidence we can gather. The further into the past astronomers peer, the fewer and the fainter the signals they receive —excluding any major events in the history of the universe, such as the CMB radiation emission—, which means only certain types of sources can be detected. The signals are dimmed because of distance, interacting with other objects while traversing spacetime, and being redshifted from the expansion of the universe (Ellis, 2007). Additionally, there is the possibility that eras of the universe are completely unobservable because of the conditions at that time, such as the cutoff point dictated by the CMB in modern cosmological models, before which we cannot observe because radiation could never escape and reach us. Moreover, observing objects from the early universe makes it more difficult to determine their properties. This is due to the faint and sparse signals we receive from such distant objects, coupled with the lack of similar nearby astronomical objects that we could use to compare. The properties of these past entities then, and the geometry of spacetime of that region are both unknown; as such one needs to impose at least one of the two to arrive at any conclusions about the other, making any knowledge of them model-dependent and thus, any testing circular (Ellis, 2007).

All of these issues make it a difficult task to reconstruct our past light cone to determine both isotropy and the geometry of spacetime. The existence of the elusive dark components adds another layer of difficulty since they are even harder to access empirically. As dark matter only interacts gravitationally, it is impossible to understand its behaviour and effects without first imposing a model, which can then be incorporated into the considerations for the observables (Maartens, 2011). A similar situation is true for dark energy, as well. Observations of these are always indirect, but because of their interaction with this spacetime geometry, it is necessary that they are also isotropic and homogeneous for the universe to be considered FLRW.

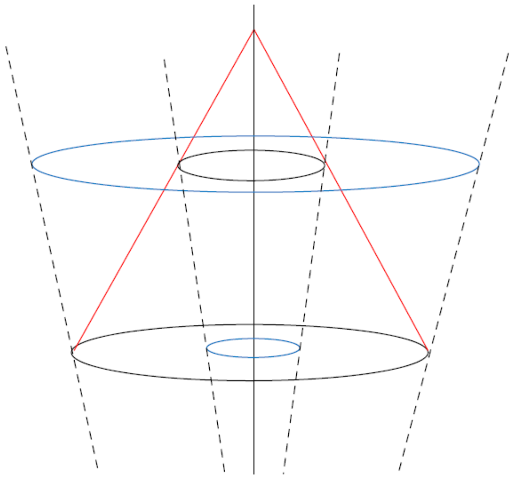

Figure 2.3: Because we can only view surfaces that intersect our past light cone we receive limited information from each time slice and cannot directly test homogeneity. Figure taken from Maartens (2011).

Establishing homogeneity has one additional unique complication. Because of our placement at a specific point in spacetime, we have no empirical access to what other observers, at different spacetime points will see, as is shown in figure 2.3. Since homogeneity is marked by translational symmetries one would need observations from distances meaningfully far in the cosmic scale from our position. This could be performed either from regions spacelike separated from ours, making them impossible to contact, or from our past light cone. Tests of homogeneity have been proposed using the latter and the CMB and they will be examined in §3.5. A multitude of other consistency tests have been created for the cosmological principle, but because of their assumption of an FLRW geometry they can only attempt to falsify but not offer genuine empirical support for the principle. Another popular way to bypass this issue is given the isotropy of our position, to argue that isotropy is viewed by all observers. If there is isotropy everywhere in the observable universe it would in turn translate to spatial homogeneity. One can claim this position by adopting the

Copernican principle.

2.4 The Copernican Principle

The Copernican principle states that our position in the universe is not privileged. Usually, ascribed to a cultural notion that came to dominate the attitude surrounding knowledge, after the adoption of the heliocentric model, which removed the Earth from the centre of cosmological constructions. This idea has historically been influential across various fields of physics. As such, a multitude of formulations of the principle exist. Today many debates on the exact ideas of the principle still persist, especially surrounding the notion of what constitutes a typical observer. This idea of the typicality of an observer is tied to attempting to give physical meaning to the terms of the principle. The notion of being privileged is not a term with physical meaning, directly translatable into mathematics (Beisbart & Jung, 2006). An observer, however, does have physical meaning within general relativity and there are ways to define what would make them special. While general relativity does not have preferred frames in the sense of construing the true state of an object, in §2.2 a preferred rest frame was defined in the context of the simplification of mathematics, which could be understood as special if unique. For the purposes of the argument for the cosmological principle, the Copernican principle can be reformulated to refer only to the observations an observer can conduct, with primary consideration to the distribution of matter. This would mean that our observations are representative of the larger class of possible observations the various observers in the universe can make (Roush, 2003). If observations are isotropic around our position, and we are not in a special position within the universe, all observers would view a similar isotropy.[5] This means that around every spacetime point, there is isotropy, making the universe necessarily homogeneous. The idea can be extended with the four observable quantities mentioned in §2.3 that can showcase the isotropy of the geometry (Maartens, 2011).

Adopting the Copernican principle is not a straightforward solution. It is often justified using Bayesian probabilities, that is, it is highly unlikely that we live in a special position in the universe, such as the centre, from which potentially the universe could look isotropic but be inhomogeneous. This strategy is not necessarily convincing, because it is unclear whether the priors under consideration are that high. A counterargument often mentioned, to show that those priors can be low, appeals to the anthropic principle or the idea that our position in the universe must have the necessary preconditions for the existence of observers (e.g. Kanitscheider, 1991). Building on the previous example, it may be that in our universe, those conditions are only met near its centre and that is why we as observers exist here, which transforms our position from highly unlikely to very probable. This idea specifically targets the notion that we are typical — not special — observers, by attaching special features to our existence. One can define an equivalent class of observers and reformulate the principle to tackle this issue, but this shows how difficult Bayesian probability justifications are.

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[5] One could say that in an inhomogeneous and anisotropic-in-every-position universe, all positions are special as they are unique, but the discussion here usually revolves around the complexity of the mathematics, as in general relativity there is no true privileged frame in the Newtonian sense.

A similar argument is offered from the modelling perspective. There is a multitude of models with different parameters that can potentially fit observations that are inhomogeneous and only isotropic around our position, or the converse. It is unclear whether they are more numerous than the class of FLRW models and thus, from a Bayesian perspective, one cannot be certain which type of model is more likely to represent our universe best (Beisbart & Jung, 2006). The effectiveness of the application of Bayesian epistemology, in general, is a whole separate issue and discussions surrounding probabilities, especially in the context of cosmology, where we have evidence only from one observer location and only one universe, can degenerate quickly. This is because one could argue there is a lack of a good probability measure when the sample size is one and the initial conditions are unknown and it is ambiguous how to even interpret such a measure with only a single realisation of the universe known. The Copernican principle is, thus, in unstable footing if not assumed a priori.

A strategy out of this predicament is to select a global rest frame. By identifying such a frame, all observers would have a time slice they could refer to that would allow for their comparison. As it was mentioned before (§2.3), however, because of general relativity, a spacetime structure can only become global when certain choices are made, such as the FLRW metric, which allows us to identify global symmetries. Cosmologists identify a global rest frame with the CMB, which means they assume as a rest frame for all observers the one where they view an isotropic CMB. That is an assumption though that supports the Copernican principle in a circular way, unless it can be backed by empirical evidence. This is one of the many applications of the CMB that mark it as a significant event in the history of the universe for cosmology, and on which I hence turn my focus.

Chapter 3

The Cosmic Microwave Background and the Cosmological Principle

3.1 The Cosmic Microwave Background

The CMB is one of the best-understood and most well-established cosmological phenomena. It is widely considered by physicists as one of the best probes of the early history of the universe. Its detection is considered one of the most important pieces of evidence in favour of the widely held understanding that the universe began with a Hot Big Bang. According to Big Bang models, in the early stages of the universe, the temperature was so high that all matter was in a hot dense plasma state. Photons were continuously absorbed and remitted by protons and electrons. As the universe expanded, it began to cool down and around 380 000 years after the Big Bang it entered what is known as the era of recombination where protons and electrons could combine to make the first atoms. When these charged particles combined and stabilised, the number of photons scattering rapidly diminished resulting in many of them travelling through spacetime, to reach the Earth of the present. Because these photons were travelling through the expanding universe before they reached us, during their journey they got stretched alongside space, which redshifted them to the microwaves we detect today.

Since the 1980s, space agencies have been periodically sending observatory telescopes on satellites to study the CMB more comprehensively. Putting them into orbit has the benefit of avoiding potential noise generated on the Earth, missing signals getting blocked through interactions with the atmosphere, and surveying the whole sky with the same instruments. The Planck spacecraft was the latest such mission and the analysis of the entire set of data was completed in 2020, giving the most comprehensive cosmological parameter estimations from early universe data to this day.

As the CMB is the oldest evidence astronomers have access to, since before recombination the universe was opaque, it is one of the few ways to test any hypotheses about the early universe. Analyses of the CMB are largely responsible for our knowledge of the matter composition of our universe. The power of the CMB lies in its high energy at the moment of emission, as it allows for tests at energy levels that are unthinkable in terrestrial physics. It does have its limitations, however, most importantly the microwaves that arrive in telescopes are very low energy and any high-energy test requires extrapolation back in time. Idealisations are also necessary, such as assuming that the emission of the photons happened everywhere from a single spatial scattering surface in a snapshot in time, even though, the process was not instantaneous.

3.2 The (An)Isotropy of the Cosmic Microwave Background

3.2.1 Decomposing the Cosmic Microwave Background

Despite the limitations the CMB offers quite a substantive framework from which we can study questions, such as the isotropy and homogeneity of the observable universe. All the successive missions have provided support for the isotropy of the radiation detected from the CMB (CMBR). The temperature of the CMB appears to be uniform with fluctuations in the range of $\frac{\delta T}{T} = 10^{-5}$, making the CMB a near-perfect black body with a temperature of 2.7 Kelvin. While the range within which the isotropy of the CMBR breaks is small it can still be a cause for concern unless the fluctuations can be explained.

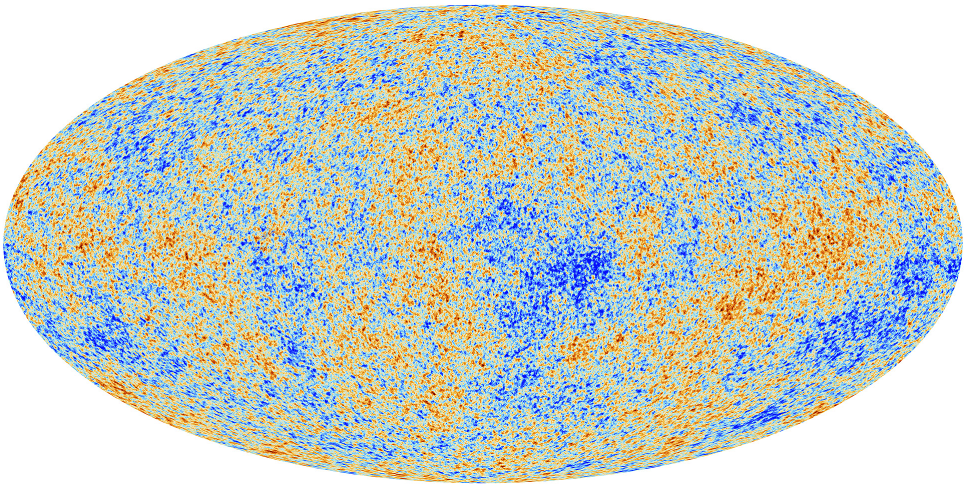

Figure 3.1: The anisotropies of the CMB. Figure by the ESA and the Planck Collaboration.

In order to explain the fluctuations and understand the nature of the CMB astronomers utilise statistical analysis. They specifically apply multipole analysis decomposing the signal into spherical harmonics. Spherical harmonics are orthogonal functions that are defined on the surface of the sphere. Their use is necessary because the CMBR is viewed from the Earth as a 2-dimensional shell surrounding it. Using different angular scales of analysis the surface of the CMBR sphere is broken into a different number of patches or poles, described by the spherical harmonics. Spherical harmonics are given by

$$f(\theta,\phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\phi) \tag{3.1}$$

In the case of the CMB

$$f(\theta,\phi) = \frac{\delta T}{T}(\theta,\phi) \tag{3.2}$$

where θ and ϕ represent the angles in the spherical coordinates T is the temperature and

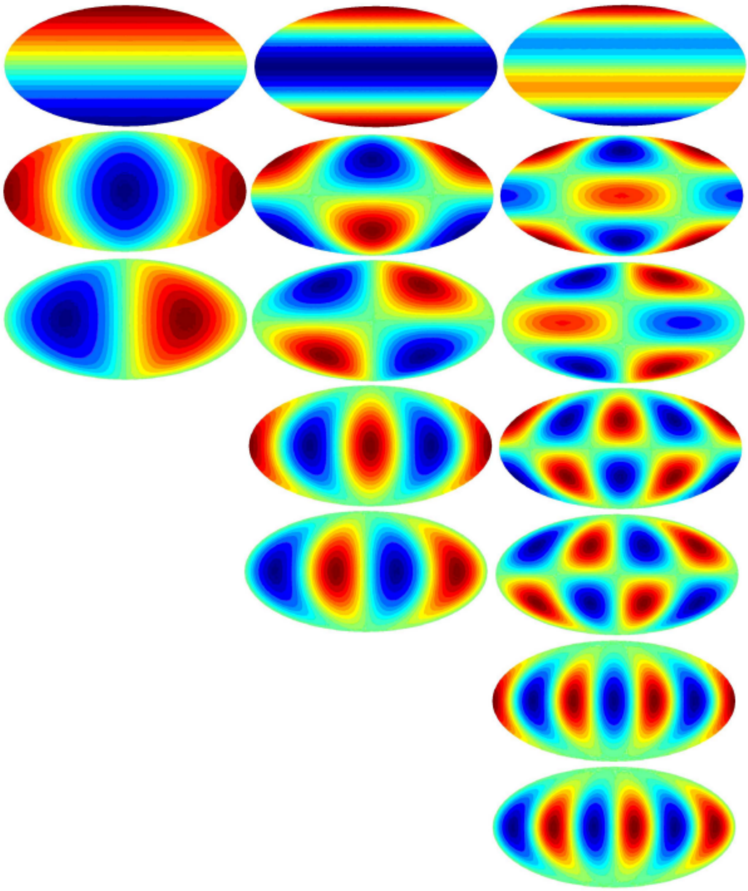

Figure 3.2: Representation of spherical harmonics. From left to right, each column shows the multipoles from $l = 1$ and increasing. From top to bottom, each row shows the mode starting with $m = 0$ and continuing with $m = \pm 1$ and so on. Figure by Ville Heikkilä, taken from Hannu Kurki-Suonio's lectures on cosmology.

δT are the fluctuations.

Multipoles have a moment l that represents the angular scales, beginning at $l = 0$ which is the monopole and increasing values of l decrease the angular scale progressively creating finer regions. From the nature of the spherical harmonics, the multipoles created are of the power of two, thus $l = 1$ is a dipole, $l = 2$ a quadrupole and so on. Lower multipole moments showcase larger-scale fluctuations while larger moments correspond to smaller-scale fluctuations that are caused by minor sources. Spherical harmonics are also dependent on the mode m which spans from $-l$ to l and determines the shape of the patches that are defined on the sphere's surface. Similarly to a Fourier series, adding all the infinite multipoles should converge to the initial picture of the CMBR. A representation of low multipole moments can be seen in figure 3.2.

The goal is to calculate the coefficients in order to understand how much each spherical harmonic function or each multipole contributes to the observed signal. From equations (3.1) and (3.2)

$$a_{lm} = \int Y^*_{lm}(\theta, \phi) \frac{\delta T(\theta, \phi)}{T_0} \, d\Omega \tag{3.3}$$

where $d\Omega = \cos\theta \, d\theta \, d\phi$.

3.2.2 Assumptions and the Power Spectrum

An important assumption made when conducting this analysis is that the fluctuations are of a Gaussian nature. This means that the expectation value of the coefficients is zero

$$\langle a_{lm} \rangle = 0 \tag{3.4}$$

An additional significant assumption, made in this analysis is statistical isotropy, which is used to simplify the statistical analysis of the data when calculating the fluctuations of the CMBR function. This means that the coefficients are independent variables:

$$\langle a_{lm} a^*_{l'm'} \rangle = 0 \tag{3.5}$$

and the expectation value of the two-point correlation function is zero.

In order to calculate the fluctuations astronomers derive the power spectrum C_l, which represents the strength of the fluctuations of the CMB for each multipole. Essentially, it quantifies the temperature difference from the average at different angular scales. The power spectrum is defined by the coefficients of each angular scale, which define the contributions of individual multipole to the general CMBR function. By assuming isotropy one can average over all the different m modes for each multipole, as no matter what the orientation of the pattern made from the patches of the sky is it should have statistically the same properties. Taking into account statistical isotropy the theoretical power spectrum C_l is defined as the expectation value of the squared multipole coefficients:

$$C_l = \langle |a_{lm}|^2 \rangle \tag{3.6}$$

where the coefficients only depend on l. The CMBR is then understood as realised by an underlying Gaussian isotropic process, of which there are many possible realisations that are statistically isotropic and we calculate the variance (Bucher, 2015).

The observational power spectrum C_l^{obs} is estimated from the observed a_{lm} coefficients:

$$C_l^{\text{obs}} = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2 \tag{3.7}$$

which is not an expectation value since there is only a single realisation of the CMB in the universe, giving a sampling size of one to compare with the theoretical statistical values.

This is vital because astronomers only have access to information on the CMB from one universe, and thus limited data points. In statistical analysis normally multiple realisations of an effect are considered and then the averages are extracted. With a sampling size of one, it is impossible to calculate expectation values unless astronomers average over the m modes, which is what they do. This creates large uncertainties on lower multipoles, where the sampling size is smaller due to the lower number of m modes as shown in figure 3.3. This phenomenon is known as cosmic variance and is the effect on observational data of having only a single universe. One might ask why is it not possible to simply determine the individual contributions, and why astronomers use statistics to understand the CMB. This is because it is far more efficient to discuss the statistical properties of the CMB when considering all the noise and complexity, something that will become apparent in §3.3. For now, it is important to note that if astronomers did not assume isotropy they would have to work with a more general probability distribution that has more parameters than observables, making it challenging to obtain useful results (Bucher, 2015).

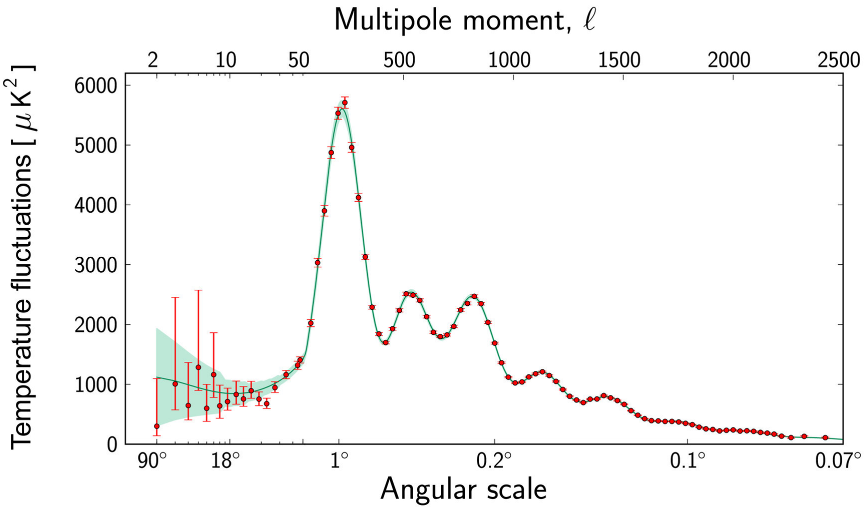

Figure 3.3: The CMB power spectrum C_l plotted over the corresponding multipole moment l and the angular scale. The red dots represent the measurements and their error bars, the line shows the theoretical expectations of the power spectrum, and the green area demonstrates the expected cosmic variance error. Figure by the ESA and the Planck Collaboration.

The power spectrum depicted in figure 3.3, therefore, maps out the fluctuations on each possible scale. Larger angular scales showcase fluctuations of a bigger size in the CMB sky, and smaller scales show the converse. The y-axis represents the intensity of the fluctuation. Figure 3.3 illustrates the existence of some anisotropies, that demand an explanation. The fluctuations are attributed to two types of effects: intrinsic fluctuations of the CMB and effects that alter the propagating radiation as it travels towards the Earth.

The intrinsic fluctuations of the CMB are considered a vital puzzle piece in modern cosmology, as in a perfectly homogeneous and isotropic universe all observed structures in the universe would not be able to form. Thus, cosmologists assume the existence of primordial density perturbations of matter. These perturbations allowed matter to clump together and create observable structures, such as galaxies. Ideas differ on how these fluctuations came to be, but the important thing is that they were present in the early universe.[1] An important effect here is the Sachs-Wolfe effect which is the dominant

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[1] In cosmology the major camps on the matter either attribute the perturbations to the initial conditions of the

contributor to the anisotropy peaks at most angular scales. During their emission, photons in overdense areas had to climb out of larger gravitational wells, resulting in an energy loss that is imprinted on the CMB as temperature differences.

On the other hand, while the CMBR is propagating through the universe physical influences can have noticeable effects on it. As I already mentioned one of these effects is how the expansion of the universe stretches the photons into microwaves by the time they reach our detectors. Other effects include gravitational lensing and the integrated Sachs-Wolfe effect. These types of effects, while significant to the theoretical prediction of the power spectrum, generally have small contributions. The most consequential one comes from the integrated Sachs-Wolfe effect which primarily contributes to the first peak of the power spectrum. This effect describes how photons travelling through spacetime encounter numerous gravitational wells. As photons fall into these wells, they gain energy, which they subsequently lose while climbing back out. However, the depth of these wells can change while the photon is within them, leading to additional energy gain or loss. Astronomers account for all these theoretically treatable effects and create the theoretical expectation of the power spectrum, explaining why certain multipoles exhibit larger fluctuations.

In all power spectra, the monopole and the dipole are excluded. The monopole is interpreted as the mean temperature because it results from averaging over the whole sky. In a perfectly isotropic CMB, the monopole would be the sole contribution. This means that the monopole scale represents no fluctuation, as it matches the expected value of the CMB temperature. The dipole, on the other hand, possesses significant cosmic variance and represents the largest anisotropy of the CMB. In an FLRW universe, one would expect if the Earth was moving in accordance with the rest frame of the CMB that the CMB would appear completely isotropic. However, that is not the case observationally. This discrepancy is attributed to the movement of our local neighbourhood relative to the rest frame defined by the CMB because locally the universe is inhomogeneous (Aluri et al., 2023). As such, any large-scale density perturbations that would have left a signature on the dipole are dominated by the anisotropy caused by the Doppler boosting of the Earth's motion. It is impossible to separate them because all dipole contributions are linearly dependent and result in only one observable dipole in the CMB sky. Therefore, the dipole is not considered in investigations of the power spectrum to understand the various cosmological effects.

As is shown in figure 3.3 the theoretically expected values of the CMB match to a very high degree what is observed. These theoretically expected values are constructed through simulations of FLRW universes with specific initial conditions while factoring in all the effects that left a mark on the CMB. The theoretical values are built on the assumption that the CMB appears statistically isotropic to all observers comoving with its rest frame. The whole model alongside the assumption can be tested through comparison with the data from observation. As was mentioned already, however, the analysis of the CMB also uses as a precondition the statistical isotropy of our observations of the CMB. Therefore, while the correspondence of data and theory showcases consistency, the observations cannot be taken as directly confirming an FLRW evolution of the universe. There is a circularity

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universe or from some general initial conditions they use a smoothing mechanism, usually inflation, that results in a perturbed FLRW universe.

here, but it is not necessarily vicious if the statistical isotropy can be independently shown. Demonstrating statistical isotropy is vital even beyond breaking the circularity because as discussed above, not assuming it will remove the ability to average over the m modes diminishing the reliability of the observational data analysed through spherical harmonics as the effect of cosmic variance gets amplified.

3.3 Isotropy Tests from the Planck Mission

3.3.1 Cosmic Microwave Background Radiation Detection and Data Analysis

The Planck mission is a collaboration of numerous research groups and institutions with the goal of understanding the CMB as well as possible. The methodology they utilise is highly complex, to ensure the minimisation of errors and the accuracy of the results. It is, therefore, impossible to consider here in detail how the CMB data is analysed and interpreted, as this is done in tens of papers published by the Planck collaboration. For the benefit of the reader, a simplified schematic representation of the most relevant aspects of the data analysis pipeline of the CMB is presented in figure 3.4.

The Planck satellite receives radiation signals, in the form of microwaves, by surveying the whole sky. The raw data itself is of little use to astronomers, without any further processing. Instead, a long and complex data processing pipeline transforms the data from the signals that the instruments detect to models.[2] Astronomers construct data models based on data calibration and simulations to remove noise and extract only the relevant data. Refining data is not necessarily epistemically suspect. It can often make data sets more reliable, through the removal of unwanted effects and their transformation to data that can be compared with the theoretical predictions. This process of transforming data into a data model is prevalent in High Energy Physics, as well, another epistemic activity where the experimental data cannot be immediately compared to theory without some form of processing (Antoniou, 2021).

In the Planck collaboration, there are three levels to this process. In the first level, the data from the satellite and the mission control are gathered, and the ones that are faulty are removed. The Placnk satellite has two detectors: a High Frequency Instrument (HFI), responsible for detecting signals with frequencies between 100 and 857 GHz and a Low Frequency Instrument (LFI), which probes the frequency bands between 30 and 70 GHz. Detecting signals for two different frequency ranges increases the data volume that can be utilised to detect the CMB accurately. The CMBR is theoretically expected to be more intense in the 70GHz to 217GHz range. The second level involves the creation of calibrated maps from each detector transforming the voltage signal into temperature and removing systematic errors. There are issues that both suffer from, such as problematic data produced by satellite movements and information that gets lost during transport, and detector-specific issues, such as spurious signals at specific frequencies (Planck Collaboration II, 2020; Planck Collaboration III, 2020). In the last level, both the HFI and LFI maps are combined

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[2] More information can be found in the Planck collaboration papers (Planck Collaboration I, 2020).

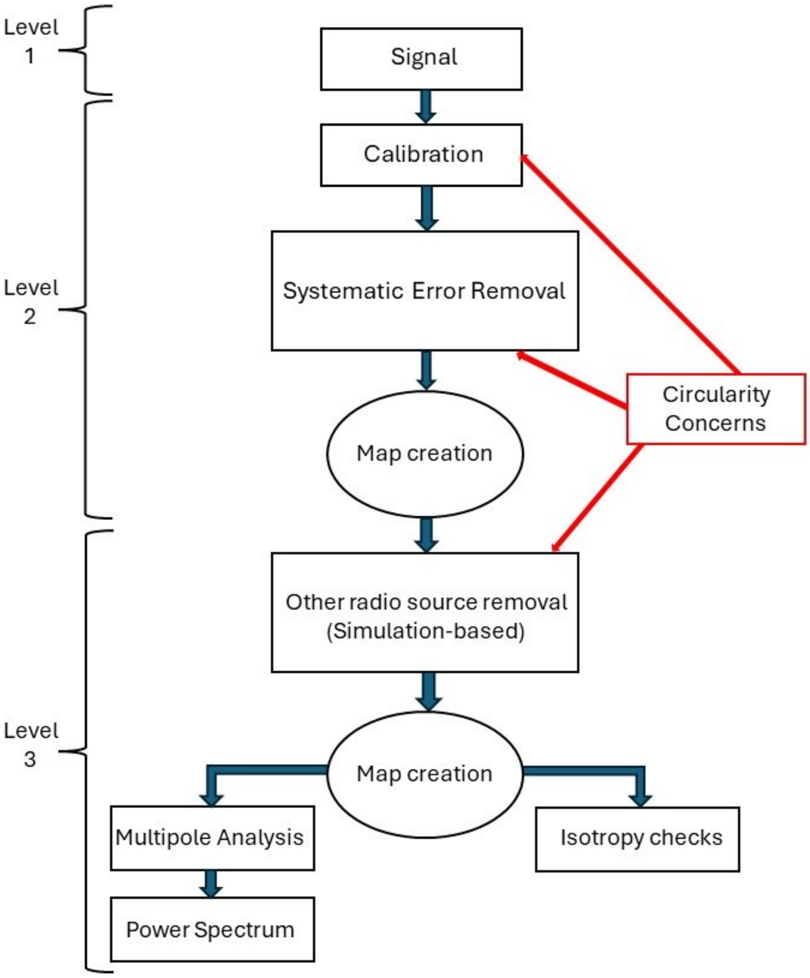

Figure 3.4: Simplified Planck data processing chart

and the CMBR signals are separated from sources that emit similar signals in the observable universe, such as galaxies and quasars, through simulations to calculate the power spectra, check for isotropy, and determine the cosmological parameters in the early universe.

3.3.2 The Dipole

Calibration is an important part of second-level processing, using well-established astronomical observables to ensure the accuracy of signal transformations from raw voltage outputs into thermodynamic temperatures. Apart from neighbouring structures, the most important calibration method is the CMB dipole. Because of its prominence as a feature in the CMB data, it might seem like the perfect candidate to be used as a reference point. This, however, at first glance appears circular. Using the expected observed values of the CMB to calibrate the instruments that are supposed to detect is suspect. The assumption here is that, in order to identify the dipole with the movement of the solar system relative to the rest frame of the CMB, there needs to be a frame in which the CMB appears isotropic and has a specific, well-defined temperature. Therefore, what astronomers do when they estimate the dipole is to identify the Doppler boost, caused by local motion, compared to the average temperature given by the monopole.

The first calibrations of the Planck mission were performed using data from older missions studying the CMB (Planck Collaboration IV, 2014). Later iterations made use of the orbital dipole, which is the variation on the dipole caused by the Planck satellite's movement around the barycentre of the solar system. The satellite's velocity as it orbits the sun changes with respect to the CMB rest frame or the monopole even if the whole of the barycentre of the solar system is moving relative to the frame at a constant rate. This modulation can be determined by astronomers with minuscule errors and because of this, it is used as an absolute calibration tool (Planck Collaboration III, 2020).

A calibration procedure such as this is not necessarily circular. If the calibration is done purely with older observational data, then the issue becomes dependent on the way the dipole was determined on those earlier missions. It need not be an issue because it is technically possible to detect the value of the dipole, without attributing to the dipole or the monopole any specific physical significance. The only restriction is the accuracy with which the monopole can be known, independently. Identifying, however, the dipole with the Doppler boost from the frame on which the CMB is isotropic, and as such attributing specific physical significance makes this an issue.

According to (Planck Collaboration V, 2014)

$$V_{\text{out}}(t) = G(t) \times \left[B * (T_{\text{sky}} + D)\right]_{x(t),t} + M \tag{3.8}$$

where:

- $V_{\text{out}}(t)$: the output voltage measured by the detectors at time t.
- $G(t)$: the transfer function, representing the overall gain of the instrument at time t.
- B: the beam response of the instrument.
- T_{sky}: the brightness temperature of the sky, including the CMB and galactic/extragalactic foregrounds.
- D_i: the dipole signal, including the solar and orbital terms and their associated kinematic quadrupoles.
- $x(t)$: the direction of the beam axis at time t.
- M: an offset term (monopole), including instrumental offsets.

There are three main contributions here: the offset of the monopole, the relation of the beam response of the instrument and the temperature, and the relation of the beam response instrument and the dipole.

From equation (3.8), one can see that the dipole is considered a distinct contribution, different from the observed temperature T_{sky}. This means that in this model the dipole is identified with the local dipole compared to the CMB rest frame. If it was not, dipole contributions would also need to be considered as part of T_{sky} and the fluctuations that define it. There is a circularity at play here, which falls back on if we can define a rest frame, on which the CMB appears isotropic. While the intensity of the dipole means that it is a clear feature in observational measurements, astronomers can choose any rest frame from which our local motion diverges and a dipole will always show up. Without independent confirmation of the statistical isotropy of the CMB, the attribution of the whole of the dipole contribution to the motion of the Earth is conceptually problematic. While this is a good calibration practice if the CMB is assumed to be statistically isotropic, since the dipole is the most prevalent feature of the CMB, it also means that it causes issues in determining unequivocally whether the CMB is actually isotropic. A number of small but significant fluctuations could easily be masked this way. This becomes more pronounced when we consider the tensions that some papers raise with identifying the dipole with structures in the later universe.

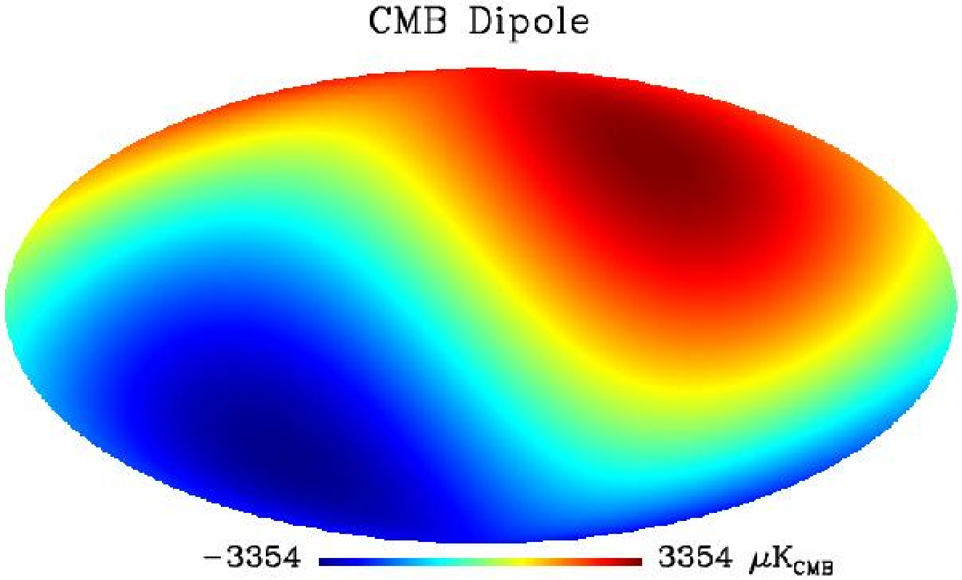

Figure 3.5: The CMB dipole as predicted through simulations. Figure taken from Delabrouille et al. (2013).

The following step as depicted in figure 3.4 is the systematic errors that must be considered and subsequently removed before the data begins to be analysed. These include the satellite's movement, its proximity to the Earth, straylight contamination and so forth (Planck Collaboration IV, 2014). Here, the dipole is removed from the data because it is assumed to be solely caused by the local motion in comparison to the CMB rest frame. Removing the dipole, as part of the systematics, means that prior to the data analyses, the biggest anisotropy has been removed. That is used, as was argued before in §3.2, to construct the power spectrum which is used as a tool for checking theoretical predictions. An argument can be made here that the removal of the dipole is necessary because even if the CMB is not isotropic, a dipole would arise because of local movement and we cannot differentiate between the different contributions to the dipole as mentioned in section §3.2.

While this is an unfortunate issue, however, it is important to repeat here that the problem lies with whether it is possible to check the isotropy of the CMB independently. When the biggest anisotropy is removed it is bound to be problematic. Therefore, using the dipole for calibration and subsequently removing it from the data appears to fall into a new circularity. The isotropy tests conducted by the Planck collaboration, however, reintroduce the dipole, as will be discussed in §3.3.4, which would allow for genuine tests if not for the calibration process. Nevertheless, for both justifying the calibration procedures and the subsequent analyses verifying the dipole independently would solve all outstanding issues.

To this end, several astronomers have attempted to show the kinematic nature of the dipole through different avenues in cosmology. The issue is twofold because both the orientation of the dipole and its magnitude do not exactly match the effect that the motion of the local group is expected to create (Aluri et al., 2023). The way this can be shown is through radio source counts, provided we live in an FLRW universe. If the dipole is entirely kinematic and the universe is isotropic throughout time, then the radio source counts are expected to show the exact same dipole as the CMB (Ellis & Baldwin, 1984). On larger scales where the local inhomogeneity caused by the local group is not considered the local rest frame should be converging with the CMB rest frame (Sarkar et al., 2009). This has not been shown, instead, some studies suggest that radio galaxy and quasar distributions are not isotropic in the CMB rest frame (Secrest et al., 2021, 2022). Moreover, some astronomers report that the Earth is observed to be part of a fast-moving bulk flow, that does not appear to have a mean approaching zero, as would be expected in an FLRW universe (Mohayaee et al., 2024).[3] In addition to this, several studies have shown an amplitude excess for the matter dipole suggesting that there is potentially a genuine tension, with some papers even suggesting it with certainty up to 5σ (e.g. Bengaly et al., 2018; Singal, 2019). While fewer in number, some scholars claim to show consistency between the CMB dipole and its radio source counterpart (e.g. Darling, 2022). Others have attempted to explain away the tension using potential previously unaccounted-for effects on the astronomical signals that could be generating systematic errors in the data. One group investigated the effect of the redshift evolution of the radio sources on the data and evaluated the necessary rate to remove the tension (Dalang & Bonvin, 2022). Another group suggested taking into account the luminosity function that has been ignored so far in derivations of the expected dipole anisotropy (Guandalin et al., 2023).

This debate showcases once more the difficulties encountered when attempting to construct a genuine critical test of the cosmological principle. Nevertheless, while the evidence appears inconclusive, many cosmologists are calling for more comprehensive studies of this through new radio source catalogues and more accurate observations that might eventually be able to settle this debate. What is certain is that the dipole has not been shown independently to have a purely kinematic nature and that it can be regarded as such when analysing CMB data. Until this can be achieved this circularity within the analysis of the CMB will remain a concern.

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[3] Bulk flows are the averaged velocities of local structures being pulled towards one another because of that local inhomogeneity.

3.3.3 Simulations

The first step of the last level in the data analysis pipeline of the Planck mission, as shown in figure 3.4, is the component separation of the different radio signals, to isolate the CMBR. This is achieved through simulations called diffuse component separation, which essentially remove the foreground from the CMB. The foreground is other sources that emit signals, which arrive on similar frequencies that the CMB is observed on. The emissions of the Milky Way galaxy and of more distant sources comprise the foreground.

There are four different algorithms utilised for the simulations, each creating its own component-separated maps. They can be divided into two categories, the ones that make predictions for the CMB with no assumptions about the foregrounds and the ones that model the foregrounds (Planck Collaboration IV, 2020). The latter methods are Commander-Ruler (C-R) and Spectral Matching Independent Component Analysis (SMICA). The Commander method used a Bayesian fitting approach that runs Monte Carlo simulations to sample a posterior distribution, based on cosmological parameters, and fit it to the data (Planck Collaboration IV, 2020). This method uses a signal covariant matrix for calculations that assume both that the fluctuations are of a Gaussian nature and that they are isotropic (Eriksen et al., 2004). SMICA creates CMB maps through the linear combination of different frequency maps with different weights for each multipole. The weight of each multipole is evaluated based on a covariant signal matrix with an isotropy assumption, similar to the one used for Commander (Planck Collaboration XII, 2014). The initial assumption of isotropy in both algorithms means that they cannot be taken alone as successfully isolating the CMB since the isotropy has not been established.

The other two algorithms are the Spectral Estimation Via Expectation Maximization (SEVEM) and the Needlet Internal Linear Combination (NILC) methods. They make no assumptions regarding the foreground, instead, utilising the expected values of the CMB to remove it. NILC functions similarly to SMICA, combining linear maps of the observed CMB at different scales and sizes, giving them different weights, in order to extract the true signal (Delabrouille et al., 2009). The difference with SMICA lies with the different scales and the way the weighting is calculated, changing depending on the position and the multipole through the use of needlets (Planck Collaboration XII, 2014). SEVEM, on the other hand, utilises the internal Planck data maps. By subtracting those of neighbouring frequency and same resolution, it attempts to isolate the CMB signal (Fernández-Cobos et al., 2012).

The main assumptions in NILC and SEVEM are that both the noise and the fluctuations of the CMB are of a Gaussian nature, something assumed in the mission itself, and that the CMB emissions are those of a black body spectrum (Delabrouille et al., 2009). This last assumption is necessary for both combining maps and comparing templates, as it factors in specifically on how the CMB signal is modelled. For NILC, without this assumption, the CMB signal would not be reconstructable through a linear combination of maps. In the case of SEVEM, in order to be able to subtract the templates astronomers assume that the CMB is a black body and thus contributes equally to all frequencies when measured in thermodynamic temperature, which means that maps of the CMB in different frequencies are expected to look the same if no foreground exists. This baseline is what allows the subtraction of two templates to result in only the foreground. This assumption can be problematic because black bodies are diffuse emitters, which means that the radiation they emit is isotropic, effectively, therefore, assuming isotropy in a different way. Once again, however, if the fact that the CMB is a black body can be independently shown, then there would not be an issue. The black body nature of the CMB has been extensively defended because of data from previous missions and because of its spectrum — its intensity follows a specific curve for each emitted frequency— making it an established fact in cosmology (Fixsen, 2009). Nevertheless, any confirmation of the black body nature of the CMB has to essentially pass through a component separation method. The situation seems to be that unless somehow we are able to know all the foreground contributions accurately and independently there is no realistic way to independently showcase the validity of this assumption. Further investigation into the exact methodology and analyses of the data from the COBE-FIRAS instrument — the mission that is claimed to have definitively established the CMB as a black body spectrum — is warranted to find out if it independently showcases the black body nature of the CMB.

All four methods yield maps with consistent results something that is relevant in the isotropy tests that follow (§3.3.4), as seen in figure 3.4, though some minor differences remain (Planck Collaboration IX, 2016). They all utilise different methodologies and different initial assumptions, to arrive at similar results. While the assumption of isotropy seems everpresent, it does not guarantee the maps' consistency, which provides a small additional basis of support for the results. On the other hand, though, the similarity is not genuinely convincing evidence because of the isotropy assumption.

3.3.4 Isotropy Tests

Scientists working within the Planck Collaboration have attempted to set up various ways to check the isotropy of the CMB. Granted what I have laid out prior in this section, any tests of isotropy that can be conducted at this point of the data analysis seem like they would fall into a circularity. This can be solved if the dipole or the black body nature of the CMB are established independently. While this might be feasible in the future, it raises the question of whether conducting isotropy checks is worthwhile. Here it is important to note, that the methods described before exhibit certain circularities, but they do not necessarily save the phenomena and, as such, fall into a vicious circularity. The assumptions, and the circularity they imply, do preclude any isotropy checks from being genuinely validating, but they do not guarantee the results. This can be seen in the power spectrum 3.3, as despite the black body and dipole assumptions, anisotropies still appear. The assumptions could be hiding part of the fluctuations, as in the case of the dipole, but they do not enforce that the isolated signal appears isotropic. Thus, the tests can be a significant part of a long list of checks of the isotropy of the CMB. At the very least they can conclude that there is consistency.

The way the isotropy tests work is by comparing the observations to simulations of the CMB from various initial conditions that lead to a statistically isotropic CMB. These simulations are called full focal plane (FFP) simulations and they utilise other cosmological parameters chosen to best match the available data within the established cosmological models, in this case, ΛCDM (Planck Collaboration XII, 2016). The baseline they provide is used to judge whether the fluctuations are significant or within the expected limits of fluctuations that this type of perturbed FLRW model allows (Planck Collaboration VII, 2020). This is a form of null-testing where a hypothesis is tested against the statistical data in order to identify if the data supports it.

The major temperature anisotropies that have been observed are a dipolar asymmetry of power (one of the two hemispheres exhibits stronger anisotropies), preference towards odd parity modes (odd monopole moments l), and a large cold spot in the southern hemisphere. The existence of these features is well-established. Because of their magnitude, however, there is a question of whether these are simply expected fluctuations within a statistically isotropic CMB or not. In principle, there is no unique way that one can separate genuine violations that could have physical origins from simple fluctuations that are covered by the statistical nature of the model, especially in larger angular scales where the cosmic variance error is substantially higher. This situation is exacerbated by the look-elsewhere effect. This effect, primarily present in particle physics, essentially occurs when a statistical analysis involves looking for fluctuations in many different places through many different methods. This increases the chance of finding a statistically significant result purely by chance (Planck Collaboration XVI, 2016). How often should statistically significant fluctuations be found so that we are kept within the bounds of what is deemed acceptable through the look elsewhere effect? The answer here is that it is unclear because there is no underlying physical model that can provide an expected prediction rate. This means that whenever there is no obvious way for a correction, there is a degree of subjective choice in the interpretation of the significance of these results (Planck Collaboration XVI, 2016).

Several consistency tests are performed, and I will summarise the main results. In many of these tests, the dipole is reintroduced, as the FFP simulations also include the expected effect of the boosting (Planck Collaboration XVI, 2016). This inclusion resolves the concerns outlined before in §3.3.2 regarding the removal of the dipole prior to data analysis, as including the dipole data from the observations and comparing it to the theoretical expectation values is a consistency test that can demonstrate potential issues. The main results of the isotropy checks are, based on (Planck Collaboration XVI, 2016)

- Statistical tests of variance, skewness, and kurtosis suggest anisotropies only at low significance.
- Lack of large angle correlations observed previously persists, especially on 3 and 4-point correlation functions.
- Lack of strong anisotropies on the quadrupole.
- Odd parity mode preference previously observed persists.
- Mirror-parity asymmetry appears when a reflection over a specific plane is considered.
- Analysing the local peak statistics shows no significant results.
- Cold Spot mean temperature remains anomalous.
- Dipolar power asymmetry persists, both in variance and angular checks, while if its directionality is anomalous is inconclusive.

The latest report utilised similar tests but focused on polarisation data and has largely backed the results of the previous study (Planck Collaboration VII, 2020). Additional checks are performed to ensure that the sky sample taken for the tests above is unbiased. Since most anisotropies arise at large scales it is shown that they persist when a larger part of the sky is considered (Planck Collaboration XVI, 2016). While the Planck collaboration has managed to check the dipole consistency, it still used data from the original calibration of the temperature. The large-scale anisotropies also mean that there is a limit to how much they can be constrained as cosmic variance increases at those scales, which includes the dipole.

These results can be viewed as further substantiated by the fact that all four different component separation maps give results closely resembling each other when used for these isotropy checks. The Planck collaboration claims that this makes the result robust. In the philosophical literature, a result is considered robust if one has shown it through different paths that are both independent methodologically and have diverse background assumptions (Stegenga, 2009). While this idea generally refers to varying experimental conditions, it is possible to, instead, consider various analysis paths of the same set of data as robust if they produce reliable results (Doboszewski & Elder, 2024). In the case of simulations, if an ensemble of different simulations converges to the same result, then the outcome is robust (Weisberg, 2006; Smeenk & Gallagher, 2020).[4] The Planck collaboration has shown through their isotropy checks that the different simulations produce similar results and converge towards showing isotropy. In that regard, they function similarly to the Event Horizon Telescope (ETH) data pipelines, which are independent methodologically and in terms of auxiliary assumptions, converging to a robust image result (Doboszewski & Elder, 2024). Where the Planck case diverges from the ETH is that while all four simulations function very differently methodologically and have different underlying assumptions, as it was explicated in §3.3.3, they, nevertheless, all assume in one way or another the isotropy of the CMB, which is the question they were attempting to prove. Technically, the black body radiation spectrum is not an isotropy assumption, however, it has isotropy as a consequence, for if the CMB contributes equally to all frequencies when measured in thermodynamical temperature, it would be isotropic.

Regardless of robustness, it is unclear whether to take the anomalies present in the data as expected fluctuations or as genuine tensions with the model. Between the dipole, the simulations, and the ambiguity that the isotropy checks provide, one might argue that proclaiming the CMB as isotropic might have been premature. This does not mean that there is evidence stacking against such an interpretation, but that the evidence provided so far, appears to be insufficient to fully substantiate the claim. Further investigations into the anomalies and the dipole are warranted.

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[4] The usefulness of robustness as an ideal in cosmology has been called into question in determining physical features of the universe (Gueguen, 2020).

3.4 The Cosmic Microwave Background as a Justification for the Cosmological Principle

As has been demonstrated above, establishing the isotropy of the CMB is not a simple procedure, however, justifying homogeneity presents novel challenges. At first glance, for a direct route that avoids testing, the isotropy of the CMB and the Copernican principle should be sufficient to establish homogeneity for that time slice. As explicated in §2.4 this statement would take the form: if our observations are not special, since our position is not, then the isotropy of the CMB we observe should be a feature of observations from other positions, as well. If that is true, then homogeneity has been established. That is not the case, however, even if all observers view an isotropic CMB it does not necessarily follow that the universe has an FLRW metric, thus being homogeneous in addition to isotropic (Maartens, 2011). For this inference to be true one needs to make an assumption about the nature and behaviour of matter. If the CMB is taken to be a perfect fluid, as described in §2.2, then the Copernican principle would be enough. The supposition of the perfect fluid, however, fixes the background geometry to that of an FLRW spacetime (Ellis et al., 2012). This creates a circularity as the assumptions about matter guarantee the homogeneity results from isotropy. For this reason, one needs to solve the nonlinear Einstein-Liouville field equations, for matter in a generic spacetime.

These calculations were first done by Ehlers, Geren, and Sachs (EGS) and were formulated into a theorem bearing their name, though it only took into account radiation (Ehlers et al., 1968). Other researchers generalised this result to include dark matter and a gravitational constant and expressed it covariantly.[5] As stated by Maartens (2011) CMB isotropy for all observers leads to an FLRW metric in that region if:

- collisionless radiation is exactly isotropic,
- the radiation 4-velocity is geodesic and expanding, and
- there is dust matter and dark energy in the form of L, quintessence or a perfect fluid

This does mean that the isotropy of the CMB can lead to an FLRW metric, provided one adopts the Copernican principle. If an observer views the CMB as isotropic all multipoles beyond the monopole must vanish, and so must their time derivatives. A stronger version of the EGS theorem only demands that the first three multipoles — the dipole, the quadrupole, and the octopole — of the collisionless radiation must vanish (be isotropic) for it to hold (Ellis et al., 1983).

Such a result is sufficient to establish the homogeneity of our observable universe because having an FLRW geometry restricts the observable evolution. Since the Friedmann equations (2.5) and (2.6) describe how the dynamics on that time slice work they also enforce the appropriate evolution, which remains FLRW. This is true with the caveat that no contributions from the unobservable universe, that are unaccounted for, have a diverging influence and that the scale factor is fully characterised by a quantity behaving similarly to dark energy, which means that it is the sole driving force behind the accelerating expansion

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[5] See references in Maartens (2011), for a full treatment of the proof see Ellis et al. (2012).

of the universe. This is vital because of the way that matter couples to spacetime in the theory. Any inhomogeneities will always lead to diverging rates of expansion, as locally, masses will be resisting the expansion to different degrees. Therefore, this strategy can establish homogeneity, if one adopts the Copernican principle. Notice that the same is not true for isotropy alone; observing an isotropic CMB, does not necessitate that the isotropy will remain in subsequent time slices. The result will depend on the general spacetime metric of that region, as isotropy does not constrain the entire metric.

Undoubtedly, though, as was discussed before in this chapter, the CMB is not completely isotropic. What astronomers might be able to show is that the CMB is statistically isotropic. This requires changes to the EGS theorem and slightly different assumptions (Stoeger et al., 1995; Maartens et al., 1995). As stated in Ellis et al. (2012) CMB almost-isotropy for all observers leads to an FLRW metric: "In a region of an expanding universe with cosmological constant, if all observers comoving with the matter measure an almost isotropic distribution of collisionless radiation, and if some of the time and spatial derivatives of the covariant multipoles are also small, then the region is almost FLRW." This theorem only assumes that radiation has perturbations and shows that the metric can be shown to be perturbatively FLRW. The biggest difference with the previous result is that the derivation of this theorem requires that on every step not only the multipoles are zero, but so are their derivatives in time. That is not something that is directly testable and thus, has to be assumed (Räsänen, 2009; Clarkson et al., 2003). In principle, using the Copernican principle it might be possible to show that since all observers see small multipoles, then their derivatives are also small, however, this remains an open issue (Ellis et al., 2012). Moreover, perturbed FLRW solutions are not necessarily stable, their evolution in time might lead to different spacetime geometries, depending on the perturbations. The statistical isotropic EGS theorem is weaker but describes a more realistic universe, however, the assumption of the Copernican principle remains a necessity, and as such it is unable to provide conclusive evidence for the cosmological principle.

3.5 Tests of Homogeneity using the Cosmic Microwave Background

Adopting the Copernican principle might be desirable in some camps, but as discussed in §2.4, any justification for it is far from being unequivocally convincing. Testing the homogeneity provided that the isotropy of the CMB is established is, therefore, the natural next step for the cosmologists who want to ground the cosmological principle in observations.

The tests are additionally significant because explaining the observed isotropy and uniform throughout space accelerating expansion of our universe is not only possible through an FLRW universe with an assumption of a vacuum energy. Alternative spacetime models have been developed, such as the Lemaitre-Tolman-Bondi (LTB) universes. These models also predict isotropy around our position, but one that is generated by the Earth being situated near the centre of the matter distribution. The inhomogeneity that they suggest is only in the radial direction, the one that defines distance in spherical coordinates. LTB models aim to explain the expansion through the inhomogeneity of the matter distribution, foregoing the need for dark energy. The success of the FLRW family of models, especially with the introduction of the perturbed variation that incorporates the statistical formulation of the cosmological principle, has relegated other models to the periphery of mainstream cosmological literature. Some LTB models, however are still considered viable alternatives.

Despite the difficulties outlined in §2.3, cosmologists have suggested a multitude of tests, with various assumptions, in order to find the best way to empirically check the homogeneity of the universe, in an independent way. The first type of test considers the relationship between the luminosity of standard candles and the expansion rate to construct a test of the curvature (Clarkson et al., 2008). In flat FLRW geometry, the radiation will only feel the effect of the expansion rate as it follows its null geodesics. This test hinges on the accuracy of the standard candles used, to calculate distances. Today supernovae are considered the most reliable, thus such tests can be potentially conducted in the future (Ellis, 2018). Another suggested test utilises redshift time drift — how redshift changes over time — and compares it to the Hubble rate (Uzan et al., 2008). The biggest issue here is determining the Hubble rate and the ages of objects independently and accurately (Clarkson, 2012). The independence and potential circularities in these tests will not be considered here, however, it might be beneficial if conducted in the future.

Specific tests utilising the isotropy of the CMB as a starting point have also been suggested. They utilise the Sunyaev-Zeldovich (SZ) effect, that is the interaction of the CMBR with high-energy electrons, usually found in the regions of ionised gas of large galaxy clusters. They interact either thermally, because of the electrons' temperatures, or kinematically, because of the galaxy cluster's velocities, resulting in the CMBR scattering again (Sunyaev & Zeldovich, 1972, 1980). The SZ effect is usually utilised to study the properties of galaxies, because of the distortions it can cause to the CMB spectrum. In principle, though, the inverse can also be applied, to observe the effect. If one knows the properties of the galaxy cluster one can study how the SZ effect causes a reflection of the CMBR into our light cone, essentially acting as a giant mirror, offering a view of the CMB from another position in spacetime (Goodman, 1995). Figure 3.6 provides an illustration of the effect.

The tests work because any anisotropies that get reflected will leave specific signatures in our CMB sky. For the purposes of illustrating the effects imagine an alien observer who lives on the galaxy cluster that can act as a mirror for the Earth observer, so in 3.6 the alien lives on the spacetime point of the first scattering and the Earth observer is in the primary observer's spot. When the CMB gets reflected from the alien's galaxy cluster, it will provide the CMBR with an energy boost, as per the thermal SZ effect, changing the observed number of photons at each frequency. This will change the CMB spectrum in a way that can be predicted by astronomers and thus, removed as part of the systematics. The major contribution of the thermal SZ as it results in energy-boosting radiation is on the monopole, making it unhelpful for testing, aside from identifying the locations of galaxy clusters through the spectral changes.

The kinematic SZ effect, on the other hand, is induced by the scattering of an anisotropic CMB — the alien observer views an anisotropic CMB — caused by the alien's local movement relative to the frame in which they could have seen the CMB as isotropic. This is the same anisotropy we expect on our CMB sky since in our local rest frame we do not view an isotropic CMB. Therefore, provided that the galaxy cluster is not at rest relative to the CMB rest frame the new scattering will exhibit the kinematic SZ effect. The local velocity will cause a dipole contribution in the reflection that needs to be considered when compared with the expected CMBR. If the alien observer views anisotropic CMBR the radiation will appear distorted in the blackbody spectrum we observe in our CMB, showcasing a difference in temperature within the patch of the sky that is reflected (Clarkson, 2012). Because two different temperature black body radiation spectra cannot be summed to form another black body spectrum, the effect can be observed (Chluba & Sunyaev, 2004). The kinematic SZ effect does not affect the distribution function of the radiation, in contrast with the thermal SZ effect, instead, it only changes the observed temperature of the black body spectrum.

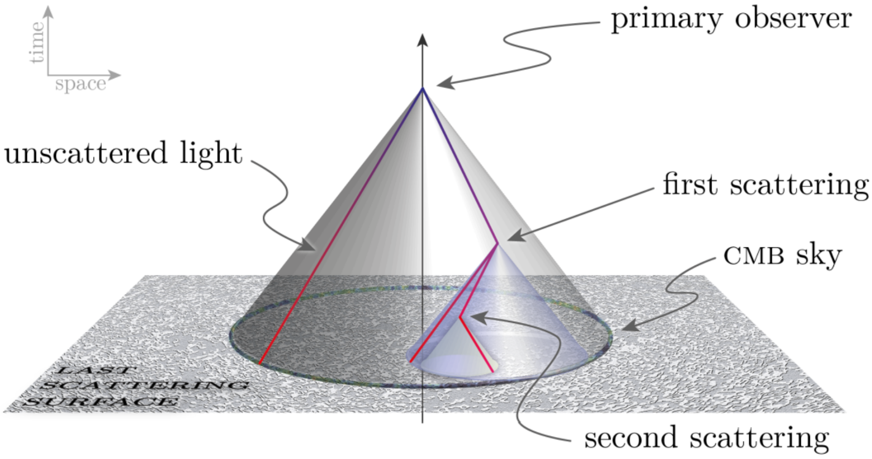

Figure 3.6: The CMBR in our past light cone can be reflected by galaxy clusters inside our light cone and to our line of sight. Figure taken from Clifton et al. (2012).

This test was first suggested as a way to constrain the radial inhomogeneities of models with the LTB metric. Any radial inhomogeneities are expected to show up as specific distortions caused by the kinematic SZ effect, since other positions in spacetime, away from the centre, should not view an isotropic CMB, even when the contribution of their motion relative to the CMB rest frame is removed. Several papers have made use of the effect to show that models that rely on anisotropic expansion caused by inhomogeneity in the late universe, even though the early universe was homogeneous, are mostly untenable (Caldwell & Stebbins, 2008; Zhang & Stebbins, 2011). These models predict that the kinematic SZ effect would be significantly more intense than the latest observations show. Effectively, this leaves only LTB models that are inhomogeneous in the early universe as credible options. Some cosmologists argue that this result largely resolves the issue of the Copernican principle (e.g. Ellis, 2018). While these tests heavily restrict previously considered viable alternatives, they do not provide direct confirmation of the principle, though, as will be discussed in §4.4, it is a way to make progress.

The next step is to ask if there are direct tests one can conduct using the SZ effect. Putting restrictions on radially inhomogeneous models is achieved by assuming the background geometry and then testing if observations are consistent. This means that while the model can fail, succeeding does not entail proving the hypothesis. The same is true for using this test in FLRW geometries. Therefore, a generalisation of this test is necessary for a generic spacetime geometry. As was described above, for the Earth observer, the isotropic CMB is indistinguishable from a reflected CMB, provided that the alien observer viewed the CMB also as isotropic. If astronomers know where the SZ effect is supposed to occur in the CMB sky, they can check whether the observations correspond. The location of the effect can be known through a combination of independent knowledge of the galaxy cluster and the presence of the kinematical and thermal effects, which will leave some form of imprint, on our CMB sky. In order to check whether the black body spectrum of the CMB is recovered, the thermal SZ effect and the kinematic SZ effect based only on the galaxy cluster's velocity will need to be removed. If the CMB is anisotropic, as observed by the alien observer on that galaxy cluster, even after removing the dipole, a different signature of the kinematic SZ effect will be left (Clifton et al., 2012). If the CMB is recovered, however, the alien observer has to have viewed an isotropic CMB, otherwise, a temperature difference in the region the cluster resides in our sky would be apparent. This test is enough to, therefore, establish isotropy of the CMB at another point in spacetime, from a single observational standpoint.

This is not enough, however, to deduce an FLRW geometry. At best what is shown here is that there is CMB isotropy around two points in spacetime. As argued in §3.4, we can use the EGS theorem, to generalise the result. The theorem, though, is only valid provided all the observers in a region view the isotropic CMB. For this result to be generalised there are two distinct possibilities (Clifton et al., 2012). Either the observer can observe the CMB for an extended period of time, enough to get information about all observers in a spacetime region, covered by our past light cone. If there is no evidence for an additional kinematic SZ effect then, that region and its causal past must have an FLRW geometry. On the other hand, if one observes CMBR that was scattered more than once, as illustrated in figure 3.6, it is sufficient to establish FLRW geometry for the whole of our causal past. This is because the alien observer (primary scattering) can only view an isotropic CMB and reflect it as such, only if the secondary scattering was also isotropic. If it was not there would be a distortion in the alien observer's sky which would then be reflected in our sky. One can then imagine this double scattering occurring throughout our past light cone demonstrating the isotropy of the CMB in an infinite regressive cycle that covers all observers in the past light cone.[6]

This result while significant, as it allows a single observer to test homogeneity, is highly idealised. It only concerns a perfectly isotropic CMB and it assumes that either double scattering is detectable or that the CMB can be observed for a long time. Furthermore, the spectral distortions caused by SZ effects are difficult to differentiate from other causes. These results, nevertheless demonstrate that there is potential in attempting to establish homogeneity even from the single point in spacetime we occupy, without falling into a

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[6] Proof can be found in Clifton et al. (2012).

circularity. In the end, the tests suggested are idealised but that does not preclude future improvements in cosmology from allowing them. If all else fails, tests can still be conducted on specific models considered viable alternatives to FLRW cosmology to determine if they agree with CMB observations.

Chapter 4

Knowledge in Cosmology and its Limits

4.1 Averaging and Fitting in General Relativity

The threats of circularity in cosmology are amplified by two interrelated problems. These issues arise from the nature of the observations and the underlying theory of cosmology, namely general relativity. Averaging and fitting put certain restrictions on the statements that can be made about the cosmological principle and on the possible tests that can be conducted.

4.1.1 Averaging

Defining homogeneity and isotropy in a way that makes them observable demands certain presuppositions. As mentioned in §2.3, idealisations are always necessary when conducting astronomical observations, especially when observations need to be comparable. This becomes relevant in the homogeneity and isotropy discussion because we cannot define them in a meaningful way without a sense of scale unless one considers them valid on all scales, a position not even the most staunch defenders of the principle can hold because of local inhomogeneities. If one attempts to showcase isotropy they need to demonstrate that the observer views the same thing in every direction. This raises the question of how much angular rotation is sufficient to constitute a new direction, essentially what is the minimum possible rotation? The answer is that no specific metric can prima facie give that information. For isotropy, one could argue that the angular difference of the highest resolution telescope can set up the constraints in observational cosmology. In homogeneity, such restrictions become less clear because of our inability to compare observations separated by spatial translation. As such we need to establish a notion of scale, large enough, for which our observations could be compared and then check on which scales the principle holds. Cosmologists often claim that homogeneity is well-established for scales above 100 megaparsecs (Mpc) and is challenged on scales above 60 Mpc (Aluri et al., 2023).[1] The scale is volumetric and is reconstructed on the past light cone using different angular scales depending on the distances from the given slice, thus, the further back in time the signals arrive from the more redshifted they are and the smaller the angular scale that is considered.

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[1] For reference, the observable universe is 28.5 gigaparsec or 285 times larger than the scale usually employed and the Milky Way galaxy is 0.027 Mpc.

Comparisons can be made on lower scales but isotropy and homogeneity generally fail according to observations.

While the cosmological community maintains the validity of the cosmological principle above 100 Mpc is confirmed, there appear to be some inconsistencies. Observations have pointed to the existence of structures that are potentially far bigger than the purported scale on which homogeneity holds. The most famous example is the Sloan Great Wall which spans around 420 Mpc, though even larger structures have been reported. This clustering of matter that extends beyond the considered scale means that certain sections of the sky will have the presence of more matter and as such create an observed inhomogeneous distribution of matter. Initially, the existence of such structures has called into question the validity of the scale, however, physicists maintain that such structures can still be accounted for within a statistical homogeneity framework. This is because such structures can be statistically expected and singular instances like these do not necessarily violate the principle (e.g. Nadathur, 2013; Marinello et al., 2016). The claim is that homogeneity can only be discussed in an averaging sense, and as such, the universe can at the very least be treated as statistically FLRW, with the existence of some fluctuations.

The concept of averaging, however, is not unproblematic in general relativity. When astronomers set up a scale, essentially what they do is cut patches of the 2-dimensional sphere surrounding the Earth, with the dimensions of the said scale. In order to make comparisons between the patches they will average the observables of what is contained within the section. Averaging a part of the sky is not trivial, though. This is because the Einstein field equations are not linear, as mentioned before in §2.2, because the curvature of spacetime affects the distribution of mass and energy, which in turn affects the curvature itself, creating what is called backreaction. Averaging nonlinear equations is usually problematic as the results will not be representative of the actual behaviour of a system, since the small-scale effects that are hidden by this coarse-graining process might have a significant influence. This means that transitioning between small local scales, where general relativity is also meant to hold, to larger scales can be problematic.

In order to show this, one can define averaging as applying an operator A to both sides of the Einstein field equations, changing the geometry through a change in the metric $g_{\mu\nu}^{\text{local}} \to g_{\mu\nu}^{\text{avg}}$ and the energy stress tensor $T_{\mu\nu}^{\text{local}} \to T_{\mu\nu}^{\text{avg}}$. This transforms the Einstein field equations (2.1) to

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} + E_{\mu\nu} \tag{4.1}$$

The nonlinearity creates an additional term because the two sides of the equations do not commute after the operator is applied to both the geometry and the matter. The term represents the effect of local inhomogeneities on larger scales through this backreaction. Beginning from a local inhomogeneous metric and progressively smoothing would be the ideal scenario for establishing the metric of the universe, but as equation (4.1) showcases it is problematic. One could bypass the averaging problem by fixing the background, but this is an ambiguous process in general relativity as spacetime itself is dynamic, so it does not offer a non-trivially obtained background on which one can easily define averaging. Assuming a uniform global curvature, such as by imposing the cosmological principle, fixes the issue but is problematic as it imposes the FLRW metric in a local setting where it clearly does not hold. It appears relatively difficult, therefore, to define in a non-circular way averaging in general relativity. There are efforts in the literature on defining averaging in a general way, but there is no consensus among the community (e.g. Buchert, 2000; Gasperini et al., 2011). The inability to define averaging hurts the ability of cosmological models to transition between scales, creating circularity threats at larger scales, since testing for homogeneity and isotropy even at larger scales assumes that the local effects are inconsequential.

4.1.2 Fitting

The alternative way to showcase the validity of the cosmological principle and the one most favoured by cosmologists is to assume homogeneity and isotropy and use perturbation theory to explain the inhomogeneities. Cosmologists admit that the universe is lumpy and as such does not exactly correspond to the FLRW model, but choose a solution that best matches it at large scales, a situation that is also known as the fitting problem (Ellis & Stoeger, 1987). The issue here is that there is not necessarily a singular best fit and even if the best fit is found its physical status is not guaranteed, as cosmologists are always trying to fit into an exact solution of general relativity, which might not be the actual state of the universe. Fitting is not an objective process, and it does involve a threat of oversimplification, for the sake of obtaining the desired result. Even if observationally, we obtain a successful model, such as the current standard model of cosmology, it is unclear if the best fit simply ignores local but important dynamics. That in turn might be what forces us to postulate entities that fix observational discrepancies such as cosmic inflation, dark matter, and dark energy. This concern is amplified by the fact that FLRW models are one of the few exact solutions to the Einstein field equations. When this is coupled with the preference for FLRW solutions shown historically, as expounded in §2.1, the fitting process comes under scrutiny.

In order to consider a realistic metric one might compare an FLRW metric $g_{\mu\nu}$ to that of an FLRW metric with a small perturbation $\bar{g}_{\mu\nu} = g_{\mu\nu} + h_{\mu\nu}$. To demonstrate this, consider figure 4.1, illustrating the example by Green & Wald (2014). For observers living on the surface of these shapes the higher the number of surfaces the left shape has the more its metric will converge to that of the sphere. Even if the metrics are arbitrarily close, however, there is nothing that guarantees that all other observables will also be converging. The curvature of the two shapes will differ, as the sphere has a uniform curvature whereas the shape has a flat curvature on each surface that abruptly shifts when moving from one surface to another.[2] This is because even if a metric perturbation might be small its second derivatives, which determine curvature, can be large. Thus, any observables that depend on higher derivatives of the metric have a dubious physical status even if the background fits well to the real universe (Smeenk, 2020). This will be further clarified in §4.4.4.

The existence of large-scale structures in the late universe translates to significant fluctuations in the matter density. As the equations of general relativity dictate the clumping of energy and matter, that will determine the local geometry, which in turn, will affect the rate at which the universe is expanding. This backreaction is sometimes cited as an alternative to dark energy (Buchert & Räsänen, 2012). Others disagree, however, claiming to show that

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[2] In the example the boundaries are rounded, for the shape to remain continuous.

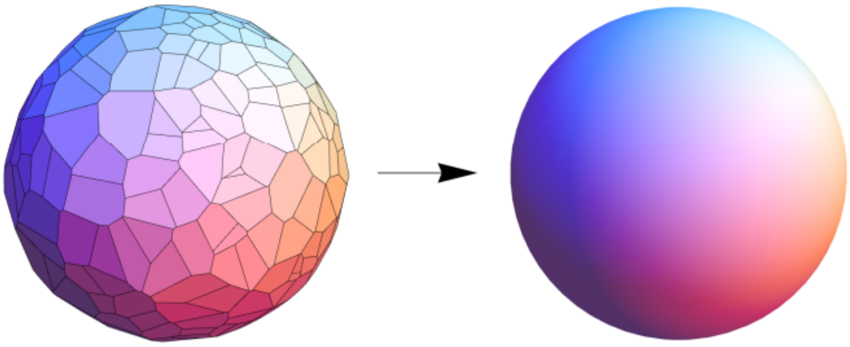

Figure 4.1: On the left there is a convex polyhedron with many uneven surfaces and on the right there is a sphere. The fitting problem is whether the right image is a good fit for the left one. Figure taken from Green & Wald (2014).

small-scale inhomogeneities are not sufficient to disturb the overall observed metric, and the large-scale dynamics (Green & Wald, 2011). While the significance of backreaction remains an open debate within cosmology, it is important to realise that averaging is exceedingly difficult, without an FLRW assumption, as without having the full distribution of matter and energy modelled one cannot be certain how the variations in the underlying spacetime will have an effect on the result (Clarkson et al., 2011). If one argues that the backreaction is irrelevant they already do it from a standpoint that accepts the cosmological principle and treats the inhomogeneities as perturbations. The only way to perform an unambiguous fitting procedure is to begin from an inhomogeneous metric and iteratively smooth it out. As described in §4.1.1 that is a challenging task.

This situation creates further concerns about the use of consistency tests of the cosmological principle. These checks are essentially fitting processes where the quality of the fit is judged. The isotropy checks conducted on the CMB by the Planck collaboration, as expounded in §3.3.4 are of this nature, as well. Demonstrating the isotropy of the CMB is the fitting of the statistical fluctuations of the CMB to the theoretically predicted results of the simulations of the standard model of cosmology. It is, thus, difficult to concretely establish whether divergences from the standard model predictions, for example in the CMB case, are an artefact of fitting a realistic universe to an exact solution of general relativity or if the tensions are genuinely physical, which makes the model's physical status also dubious.

4.2 Observations in the Real Universe

Living in a lumpy universe also affects the way that signals propagate through spacetime. As mentioned in §2.3, much of the current understanding of astronomical entities is model-dependent because the signals are understood on the basis of models. In particular, the most common assumption is that the signal travelled through an FLRW geometry to reach the Earth, thus through a homogeneous and isotropic matter distribution with uniform curvature. Signals, however, encounter all kinds of local inhomogeneities during their journey that affect their properties and in turn the state in which they are received, creating questions surrounding the reliability of our conclusions based on the observations.

In cosmology, observations are primarily of electromagnetic radiation. The geometry determines the null geodesics that the radiation follows, which are the shortest possible distance a photon can travel on the given geometry of the manifold and the path it follows if there are no external influences. The geodesic equation in general relativity defines a test particle's movement through a given spacetime as

$$\frac{d^2x^\lambda}{d\tau^2} + \Gamma^\lambda_{\mu\nu}\frac{dx^\mu}{d\tau}\frac{dx^\nu}{d\tau} = 0 \tag{4.2}$$

where τ is the proper time along the geodesic. The Christoffel symbols $\Gamma^\lambda_{\mu\nu}$ are also known as the connection because they allow us to transfer vectors from one point of the manifold to another in order to compare them. They are given in terms of the metric tensor $g_{\mu\nu}$ as

$$\Gamma^\lambda_{\mu\nu} = \frac{1}{2}g^{\lambda\rho}\left(\partial_\mu g_{\rho\nu} + \partial_\nu g_{\mu\rho} - \partial_\rho g_{\mu\nu}\right) \tag{4.3}$$

Substituting the FLRW metric, as given in equation (2.2), produces a series of equations that define a particle's path in the four dimensions of spacetime. Different geometrical structures give different null geodesics, which can lead to different reconstructions of the 3d universe from the 2d sky we observe.

Additionally, observations can be conducted on different scales, where local inhomogeneities might have a small influence on signals that are measured on large angular scales, provided that the model used is a good fit for those scales. Inhomogeneities in the radiation's path cause lensing, which can produce shear and distortion of the signals. An attempt to study the effects of light propagation in such geometry was treated with the Swiss-cheese model, a universe with an FLRW background geometry where Schwarzschild solutions of singular masses are added (Fleury et al., 2013). The authors found that observations of this model and an FLRW geometry converge the higher the cosmological constant Λ is. In principle, however many of the "apparent" parameters can differ substantially from the "background" ones.

Another aspect that must be considered in light propagation is the redshift z of the observed wavelength λ_{obs}, in comparison with the emitted wavelength λ_{em}, given by

$$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}} \tag{4.4}$$

The redshift term depends on the expansion of the universe, which stretches the radiation as it is propagating through space. The Hubble parameter quantifies the rate of expansion of the universe. For a scale factor a as in the FLRW equations (2.5) and (2.6)

$$H(t) = \frac{\dot{a}(t)}{a(t)} \tag{4.5}$$

Modern cosmology faces the so-called Hubble tension because the Hubble parameter today H_0, when calculated from early and late universe data, differs. Because of the isotropy of the expansion, the redshift z is isotropic, affecting all propagating radiation, and can be calculated as

$$1 + z = \frac{a(t_{obs})}{a(t_{em)}} \tag{4.6}$$

An instance of the necessity of these idealisations using FLRW models can be seen in cosmological distance calculation, which allows for certain isotropy and homogeneity tests. Determining the distance of the object at the time of emission generally, requires imposing a background geometry. The luminosity distance D_L is defined through the relationship between the observed flux F — energy per unit of area — and the intrinsic luminosity L of a source:

$$D_L = \sqrt{\frac{L}{4\pi F}} \tag{4.7}$$

The observed flux F depends on the amount of energy per unit of area A which is directly influenced by the number of photons that are being detected. In an FLRW universe, each photon is redshifted by a factor of $(1 + z)$ and two photons emitted at a time interval t will be measured with a time interval of $(1 + z)$ because of the expansion of the universe (Carroll, 2019). Thus,

$$\frac{F}{L} = \frac{1}{(1 + z)^2 A} \tag{4.8}$$

A different expected redshift would have produced different results.

In the case of standard candles, where the luminosity is known it appears that the issue can be solved. While this is true, standard candles have limited applicability, as they can be difficult to identify and are not present in all eras of the universe. Astronomers and cosmologists are increasingly confident that certain standard candles, such as supernovae type 1a, can be considered truly reliable indicators of distance (e.g. Ellis, 2018). As mentioned in §3.5, some tests of homogeneity have been proposed utilising them that might be possible in the near future and they are considered a great probe into the expansion rate of the universe (Clarkson, 2012).

4.3 The Methodology and Aims of Cosmology

4.3.1 Modelling in Cosmology

Despite the concerns of idealising observations (§4.2) and fitting (§4.1.2), the standard model of cosmology ΛCDM is remarkably successful at fitting the observational data with incredible precision. The main aspects of the model are its underlying theory framework being general relativity with an FLRW metric, the cosmological constant Λ and the matter contents of the universe: ordinary matter and dark matter. It is characterised by six free observable parameters and six fixed parameters. The specific choices of those parameters that make up ΛCDM can account for most observations in the larger scales of the universe.

Historical development of cosmological models followed the trajectory of the cosmological principle, as laid out in §2.1, with constant revisions to fit new observations to the models. As observations improved, FLRW models were not capable of accounting for many observations using just ordinary matter, which led to the additions of dark matter and dark energy in the theoretical framework. The observed anomalies were absorbed in the model with certain modifications, which on a Popperian reading can be seen as an unscientific process of ad hoc redefining terms and adding auxiliary hypotheses to save the underlying modelling assumptions, such as the cosmological principle (Merritt, 2017). Even Karl Popper himself denounced the Big Bang cosmological models because he considered them unfalsifiable, though prior to the emergence of ΛCDM (Kragh, 2021). The idea here relates to the fitting problem in §4.1.2, as there is always going to be a fit, the question transforms to how bad must the fit be for a model to be falsified.

In many ways, however, this back and forth is the process of modelling in physics. The model is constructed with some presuppositions about the initial conditions and the dynamical evolution, subsequently, it is compared to the target object, and if necessary modifications are applied, in essentially a feedback loop. Part of the criticism hinges on these additional postulations being ad hoc, and themselves unfalsifiable. That is not necessarily the case, however, because methodologically historical sciences, such as cosmology, function differently compared to standard experimental practice, something that will be further argued for in the following part §4.3.2. Another argument that is utilised by cosmologists to sidestep the unfalsifiability criticism is that there is a convergence towards a result in the fitting process. ΛCDM is a model that can account for most of the observations in the cosmological scales with only six parameters. It has unrivalled simplicity compared to other cosmological models, owing to some extent to the cosmological principle, is continuously verified with new cosmological data — if one ignores issues such as the Hubble tension and the Lithium problem —, and there is an absence of genuine alternatives that are not lacking either empirically or in some other theoretical virtue.[3] This type of convergence argument has been criticised in the literature because it ignores the tensions and while the convergence of the parameters follows from a multitude of different observations the parameters are not established independently of one another, creating holism concerns (Merritt, 2017).

Cosmological models have faced another line of criticism, stemming from the object of study being the whole universe. Several authors have pointed out there are conceptual problems with utilising the modelling methods of physics for the totality of the universe (e.g. Torretti, 2000; Fernández-Cobos, 2021), in addition to the issue of the universe being a unique object, the only member in its class (Smeenk & Ellis, 2017).[4] Cosmology as a discipline has often faced these kinds of debates and its scientific status has been questioned. The arguments above, however, are not necessarily effective when one takes cosmological models for what they are, models of the large-scale dynamics of the observable universe. Models that, in principle, should be allowed to have margins of error as they are concerned only with the larger scales and not with the totality of things, allowing for fitting and a statistical understanding of the model. Cosmological models are not supposed to account for every single detail of the universe through their descriptions. They are exact solutions

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[3] Modified Gravity advocates would likely disagree with this point as they see their approach as the one appealing to simplicity (Martens & King, 2023).

[4] The first problem has several ways that it can be understood and the literature is generally opaque about it. Some of them are: (i) a conceptual criticism that focuses on the fact that standard notions of modelling are not applicable since we cannot step outside the system to study it, (ii) a totality criticism since models are simplified descriptions of a target system, a cosmological model cannot account for the whole of the universe. In this thesis I only respond to the second reading.

to the Einstein field equations and, thus, can be valid to the extent the theory is valid, as is the expected behaviour of most physical models. The uniqueness of the universe remains a thorny issue, however, as a historical science, cosmology is not the only discipline that deals with a singular member of a class, something that will be further discussed in the next part §4.3.2.[5]

Understanding that the role of cosmological models is to describe large-scale dynamics dilutes some concerns about the field of cosmology and the threats that certain circularities pose. This understanding of cosmological models is not universal and the standard model has drawn criticism because it has issues with downscaling, where modified gravity theories are considered better at explaining observations because there is over-reliance on idealisations and simulations (Massimi, 2018). This is amplified by the poorly understood transition of scales as seen by the averaging problem in §4.1.1. Such an issue is of secondary importance, however, because the primary goal of cosmology is large-scale descriptiveness. It justifies the scale in which the cosmological principle is employed as it is perfectly acceptable to expect the principle to only work on those scales that the model is descriptive. This raises several questions about the nature of cosmological models and the type of knowledge they impart. The answers to these questions are defined by the types of data that cosmology has available and the ways it can employ them, which make cosmology one of the historical sciences.

4.3.2 Cosmology Among the Historical Sciences

The historical sciences do not have a unified methodology, beyond employing traces of the past to make inferences about the present. This feature, however, has been enough to call into question whether they produce epistemic goods of the same level as experimental practice (e.g. Hacking, 1989). Carol Cleland (2002) responded to these arguments, claiming that the historical sciences can still test hypotheses, as is the standard practice in physics, but by dealing with traces, instead of regularities. Such hypotheses unify the different traces and create a consistent causal story, with a common cause. The greater the number and diversity of traces the bigger the explanatory power of the hypothesis. In order to break the underdetermination often found in such empirically constraint contexts, scientists utilise smoking guns, traces that overwhelmingly suggest one interpretation. There are alternative ways to understand the methodology of the historical sciences, one of which is consilience, converging independent lines of evidence obtained from different methods (Forber, 2011). Another suggestion is that of coherence, which suggests historical scientists move beyond only looking into the relationships of traces by additionally investigating the dependency relationships of the underlying processes that produce the traces (Currie, 2018). All these different methodological interpretations can be seen as what Adrian Currie (2018) suggests is "methodological omnivory", which implies a disunited image of science, made of a patchwork of methods, evidence, and knowledge, reminiscent of the epistemological

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[5] One can deny the uniqueness of the universe with a postulation of a multiverse theory, through, for example, some inflationary model. While the existence of other universes is useful for discussing probabilistic thinking, such as in debates of the Copernican principle §2.4, it does not resolve all issues. There are still concerns about the empirical verifiability of the model when considering more than one universe. This is because, in principle, other universes are inaccessible and nothing restricts them from having entirely different physics.

anarchism of Paul Feyerabend (1993). Depending on the context the historical sciences utilise the method most appropriate for the given situation. This methodological omnivory can be seen as an asset in maximising epistemic gains when attempting to deal with the issues that the nature of the historical sciences forces upon them.

Astronomy and cosmology share many of the problems of the historical sciences. Working with traces means there is no way to manipulate and experiment on the objects of study (Anderl, 2016). The traces themselves can be scarce, indirect, or completely inaccessible. Furthermore, the problems of holism are relevant in all historical sciences as they depend on the nature of traces, which frequently disallows the isolation of hypotheses (Currie, 2018). In astronomy, specifically, several methods are used to overcome the limitations of the historical sciences. One approach is to focus on considering statistical properties as traces (Yao, 2023). Astronomers frequently average observables (§4.1.1), or consider their statistical properties when attempting to uncover their underlying dynamics, such as in the case of the CMB (§3.2). Another method employed in astronomy is the ampliative use of simulations, which involves using results from simulations as additional evidence alongside observations for testing hypotheses (Jacquart, 2020). In the literature one feature is seen as unique in astronomy, what Sybille Anderl (2016) suggests as the "cosmic laboratory". The cosmic laboratory refers to the unique situation that receiving signals from our past light cone offers. Because traces arrive from many different spacetime points, they are emitted from various sources, at different stages of their evolution, and in different environments. This allows after the determination of the properties of one type of astronomical entity to make predictions and check whether those predictions hold for other members of the same class. These can be seen as features of methodological omnivory in the historical sciences since scientists make use of any method available to them, including ones unique to the field. From the perspective of cosmology, since most data is astronomical in nature, these methods alleviate some threats of circularities that are present in other historical sciences.

The uniqueness of cosmology among the historical sciences is tied with the problems of studying the totality of all things, as explicated above §4.3.1. Studying an object that is the only member of its class is not necessarily a unique feature of cosmology, as it depends on one's definition of class. For example, the Earth is one of numerous members of the planetary class. There is, however, only one Earth; it is the sole member of the class of planets that have the exact features of the Earth. This is important because geologists and astronomers try to understand how specifically the Earth was formed and the traces they utilise come from a singular realisation. Nevertheless, there are multiple traces of different kinds and often repeating phenomena that give information that allows the reconstruction of the explanatory account of the Earth's creation. That, however, appears to not diverge from the way cosmology is conducted, with traces from various sources, giving enough information to reconstruct the large-scale picture of the universe. The only difference between the methods of cosmology and those used in studying the Earth lies in the potential to compare certain aspects of Earth's evolution with similar planets, though, the Earth still has unique features that distinguish its study from that of other planets. Even the uniqueness of the universe is, therefore, under scrutiny, as truly unique and problematic. Reconstructing an explanatory account of the universe does not necessitate having predictive laws that can be applied in various contexts, as is the case with standard models in physics. Since the idea is to describe the causal chain that led to the present, it calls for a unique account of modelling; one that does not depend on the universe being embedded in a larger system. The models from the historical sciences, as seen from the example of the Earth, are different from the models of standard physical practice but are still explanatory.

Predictiveness has a controversial role in the historical sciences. Some authors consider it a vital part (e.g. Tucker, 2004) while others suggest it is largely ignored by the scientists, in favour of explanatory value (e.g. Cleland, 2011). In many ways, traces function in a similar way to predictions in traditional practice (Cleland, 2002). While we cannot formulate our own controlled experiments the empirical data is still out there. They serve as the anchoring point of a theory and from an explanatory perspective they are what the historical science is attempting to explain. On the other hand, genuine predictions can also exist, though they might be rarer, as they require something being predicted but be yet undiscovered. One such example is the prediction of some Big Bang models that such an event would cause the CMB at a specific temperature, something that was detected a few years after the theoretical prediction (Partridge, 2019). A weaker form of prediction can also exist because the studied natural phenomena might occur more than once or allow for observations at different points in time, such as in the cosmic laboratory. In many instances, one could call features of ΛCDM predictive in this weaker sense. Cold dark matter, for example, is expected to behave in a certain way in the late universe to account for the rotation of galaxies. Evolving it backwards gives us a series of predictions on its influence on early universe phenomena, such as the CMB. The calculated physical density parameter of dark matter in the CMB — as calculated by the Planck mission from its perceived effects (Planck Collaboration VI, 2020) — needs to evolve as described by the model so it matches the value observed in the late universe.

These predictions are necessarily weaker than their experimental counterparts because of the constraints placed by the nature of the traces, which are the empirical evidence in this case. Looking into cosmology specifically it is apparent that explanatory value is considered more significant than predictions. Predictions still play a significant role in modelling, by suggesting new accounts, instead of falsifying. This explains why tensions are considered problematic but do not outright result in the rejection of ΛCDM. Instead, cosmologists continue to regard it as the best available explanatory framework for the large-scale dynamics of the universe. The explanatory value is additionally a way to bypass any circularity concerns. Provided that cosmology is creating an account of the universe's dynamics that is largely concerned with explaining, as well as possible, the observations testing independently underlying assumptions might not be necessary.

Under this reading, understanding that cosmology is concerned with describing the large-scale dynamics of the universe, and has the methodology of the historical science diminishes some circularity concerns. The historical sciences are generally speaking more concerned with explanatory value, thus making testing the cosmological principle a secondary concern. The circularities found in the isotropy checks (§3.3) and those that idealising observations create (§4.2) can make the cosmological principle impossible to test. Provided, however, that holistically the underlying model is the best available description, their importance is relegated. Fitting (§4.1.2) can be understood as a part of the methodology of the historical sciences, by creating a unified account that can be seen both in the consilience and common cause search. Questions about the exact transition between scales (§4.1.1) can also be seen as less consequential because cosmological models are only meant to describe the larger scales. All these do not mean that testing should be completely ignored, nor that the concerns of averaging, fitting, and idealising observations become completely inconsequential. After all, part of the deal of methodological omnivory is making use of every tool available to cosmology, in order to achieve progress. With the improvements in methodologies, data quality and so forth avoiding some of those circularities might be possible and this will be discussed further in the following section §4.4.

4.4 Making Progress in Cosmology

4.4.1 How Do We Make Progress?

In order to ascertain whether cosmology is a successful science, one can employ the metric utilised by much of the general philosophy of science in the twentieth century: assessing if cosmology is making progress. Progress in science is generally considered an improvement to the knowledge we have and acquiring more of it. There is a wide variety of accounts in the philosophy of science literature about what exactly this progress entails, including getting closer to the truth, attaining more knowledge and better understanding, and ideals such as unification and simplicity.[6] Quantifying the progress of historical sciences is itself a complex topic, as not having a clear unified methodology would suggest (§4.3.2). Cleland, in her accounts of the historical sciences, implies that progress is achieved through the rejection of rival hypotheses by finding the best explanation, usually through a smoking gun. Currie (2014), on the other hand, argues that there is a more complex process of synthesising simple narratives, with minimum causal detail, into complex narratives. These different understandings oppose the linear historical account of the evolution of science (e.g. Kuhn, 1975; Popper, 1959; Lakatos, 1970), with a much more pragmatic account. They identify science as a much more complicated process, progressing pluralistically, indirectly, and not necessarily with fixed goals.

Such an account can be supplemented by the operational coherence ideal defended by Hasok Chang (2022). He defines a coherent activity as one that "is well designed for the achievement of its aim, even though it cannot be expected to be successful in each and every instance". Operational coherence is about utilising procedures appropriate to the target task at hand. In the context of making progress partaking in these acts can lead to an iterative epistemic process that results in changes in many domains including methodologies, aims, and ontologies. This iterative progress has a plural character and depends on the specific context of each science, making it unique for each discipline. Epistemic iteration involves successively improving knowledge, from potentially unstable foundations, by building on the previous stages, in an effort to achieve the relevant epistemic goals.

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[6] For a review see Niiniluoto (2024).

Creating cosmological models can be categorised as a coherent activity, where the aim of describing the universe brings together different methodological and theoretical strands. They integrate fundamental theories — particle physics and general relativity — without creating a new unified fundamental framework (de Baerdemaeker, 2020). It utilises, similar to standard practices in physics, underlying theoretical frameworks and integrates empirical evidence. It, however, also has a different way of conducting its tests and is more concerned with a unified explanatory framework than precise empirical consistency. Progress in cosmology can come in different ways if it is considered with the pragmatic notions of progress. It can be defined through improving the constraints of the model and of the specific events iteratively, through an eliminative process of alternative models, and through the suggestion and discovery of new physics.

Iterative epistemic improvement in cosmology can be seen as the cyclical process identified in its modelling (§4.3.1), just as in most processes of modelling in physics. That is beginning with the original hypotheses, comparing them with observations through simulations and modelling, and reformulating the hypotheses to construct a better explanation (§2.1). The ad hoc nature criticism of the cosmological models can instead be more realistically viewed as the recognition that we cannot capture a physical system perfectly from the first attempt. Postulating entities, such as dark energy and dark matter is necessary in order to construct a better explanation. The commitment to ΛCDM, or even the cosmological principle, might be taken here as no real iterative progress in the last few decades, but that is not true. The cosmological principle itself has evolved and so have the models it inspired. While the commitment to it may require change, as will be discussed in §4.4.4, there has been progress using it, progress that might demand that the principle be abandoned.

Additionally, there is development in the methodologies, reflecting the methodological omnivory (§4.3.2), which results in the iterative progress of the models. This progress comes in the form of better constraints on the parameters and clarifying the tensions, highlighting which demand explanations. Taking advantage of all the available epistemological tools to achieve the best outcome is apparent in the simulations and isotropy checks, in sections §3.3.3 and §3.3.4. Several consistency tests are performed on the data, that are processed and checked carefully. The tests exhibit remarkable consistency across the different methods and match well with the underlying hypotheses. What few inconsistencies are observed have been at the forefront of cosmological research in order to find resolutions for them. All these models and tests have been improved through years of iterative development that comes both as new proposals and as suggestions for improvements. This is something that is true for the whole Planck collaboration, including the many different aspects of the mission that have not been covered in this thesis, and of which figure 3.6 does not do justice. Many of the decisions within the Planck collaboration were guided by work selected from earlier publications, among numerous suggestions, which received broad approval and support from the cosmological community, as well, as improvements from the previous missions of COBE and WMAP. Therefore, there is a massive collaborative effort trying to minimise errors and maximise epistemic gains as much as possible. These algorithmic and methodological improvements occur within the community, from researchers working years on the same issue, resulting in iterative epistemic gains in understanding the CMB and by extension the cosmological principle and ΛCDM.

Eliminative reasoning is another potential tool that can be utilised in cosmology. It partly reflects how Cleland (2002) understands the methodology of historical sciences of adopting the best explanation, but also more traditional accounts of progress where the accepted framework is the one that is more effective in solving problems (e.g. Laudan, 1978; Kuhn, 1975; Lakatos, 1970). In cosmology describing the large scales of the universe consistently requires an exact solution to the Einstein equations, one that can be fitted with the data from the observable universe. Throughout the years, many cosmological models and variants of the cosmological principle were discarded because they did not fit well with the data and did not provide a better explanation, for example, the steady-state model §2.1. The use of various tests, in contemporary cosmology, to constrain and rule out other models, such as the promising LTB models was illustrated in §3.5. Eliminating alternative models can happen either on the basis that they do not fit the empirical data sufficiently well — by having more tensions than alternatives or being completely incompatible with certain traces — or through being a substantially worse explanation. For the latter, several epistemic virtues might come into consideration. Some alternatives, such as the early-universe-inhomogeneous LTB models, though considered less desirable due to their complexity, remain potential choices. The best way to eliminate such alternatives is further testing and new data that rule them out completely.

Suggesting and validating new physics is an additional way of making progress in terms of fruitfulness, as it provides new avenues of research. In the past few decades, research into dark matter and dark energy has proliferated, resulting in various models and conceptual understandings. New physics can be understood as resulting in both iterative and eliminative progress. The former in the sense that similarly to the models that suggest them, they are continuously debated and refined to be a better explanation by unifying all available evidence. The latter appears through the elimination of various models, for example of dark matter, through different experiments completely independent from cosmology. Concerns arise, though, because dark matter, for instance, has been a framework that has been part of the standard cosmological models for decades but it has not been conclusively established. Unless, however, better alternative accounts arise either of physical entities or of cosmological models that do not require dark matter, there is little reason to abandon the endeavour. Such a position has been supported in the literature, as well, when considering the challenges of dark matter in small-scale simulations (de Baerdemaeker & Boyd, 2020). Until simulations are comprehensive enough physically that the empirical inadequacy becomes unjustifiable or we reach our technological and practical limits de Baerdemaeker & Boyd (2020) suggest we should keep being patient. Establishing the new physics that ΛCDM points towards would lend additional support to the model and by extension the cosmological principle.

4.4.2 Cosmology and Progress

Progress is, therefore, possible in cosmology, iteratively, eliminatively, or through new physics. This progress can be achieved in many ways within the discipline itself. Improvements in the practice and in close proximity to it can allow all types of progress to be achieved.

These can be developments in the methodology, the technology, and the theoretical basis or any combination of these.

Similarly to other historical science, cosmology can move beyond the limitations of traces. The use of simulations has already been discussed in the context of the CMB in §3.3.3. Astronomy and cosmology employ simulations to realise the models, allowing them to test the hypotheses with the observable data. The isotropy checks described in §3.3.4 use the ΛCDM model realised through simulations to compare with the observed data. This allows for testing in the weak predictive sense mentioned in §4.3.2. Another methodological difference in astrophysics specifically can be seen in laboratory astrophysics. This relatively new discipline has the ability to conduct controlled experiments, providing another avenue to practice astrophysics. Whether one views the observational and experimental practices as distinct or as Nora Mills Boyd (2023) as the same framework, the experimental results require arguments of similarity or analogical reasoning. These have their own points in question but they represent one more way to make epistemic gains. Cosmology benefits from the practices of astrophysics as progress in understanding astronomical entities allows for more precise tests, both for the cosmological principle and the standard model.

Technological innovation plays a pivotal role in the progress of cosmology. New technologies assist in uncovering lost traces or enhance degraded ones extracting more information (Cleland, 2011). Many cosmologists herald this century as the era of precision cosmology, where data is plentiful and error bars are continuously shrinking. Improvements in electromagnetic detectors, satellites, and beyond translate to more numerous and higher-quality observations. These allow more precise testing of cosmological models and determining observables, including the dipole tests mentioned in §3.3 and potentially the homogeneity tests considered in §3.5. Many of these tests were considered impossible in the past. Technological and methodological innovation has also led to the detection of gravitational waves, indicating the potential of multi-messenger astronomy. It is in principle now possible to receive more than one independent type of signal from astronomical entities, as gravitational signals can now be detected in addition to the usual electromagnetic radiation, at least for some sources. As technology improves, it presents another exciting prospect of more reliably constructing models through either consilience or common-cause arguments (Elder, 2024).

Theoretical developments both within physics and cosmology, represent one more way to make progress. In particular, theoretical cosmology has flourished, significantly improving our understanding of observations and suggesting possible tests for the cosmological principle. The observational cosmology theorem, the EGS theorem, and the homogeneity tests discussed in §2.3, in §3.4 and in §3.5 respectively are clear examples of defining the limits of the discipline and demonstrating where improvements are necessary in order to construct relevant independent tests. Developments in other branches of physics can have an impact on the progress that cosmology is making, as well. Dark matter models and their testability are one way of making progress through new physics. Moreover, further understanding averaging and fitting in general relativity will be an important aspect of solving those issues and establishing cosmological models on safer epistemic grounds.

4.4.3 How Do We Escape the Circularities?

In section §4.3.2, I suggested that circularities can generally be seen as less impactful in cosmology, in comparison with other methods in physics, because of the nature of the methodology. This does not mean, however, that establishing independent lines of evidence is not more epistemically desirable. While some philosophers of historical sciences defend them and put them on equal ground to the experimental sciences (e.g. Desjardins et al., 2023), it is beyond this thesis to engage in such debates. I maintain, however, that the traditional accounts of science are not reflective of the practice of cosmology, which has some fundamental differences from standard experimental practice and should be, therefore, evaluated differently, in these stories. Nevertheless, while cosmologists do their best given the context of their discipline, it must be admitted that where there is the potential for following more closely the experimental sciences, it would be regarded as epistemically preferable. Thus, when it is possible to avoid the circularities, one should choose to do so, as it would only strengthen their explanatory account, by independently establishing aspects of the models. Escaping the circularities is one more way to make progress, and potentially one of the strongest ones available to cosmology. Within the methodological omnivory and operational coherence accounts there is no reason not to utilise such a process that furthers our epistemic goals. Independently establishing the validity of the cosmological principle would make it a smoking gun, allowing the rejection of many alternatives,

Progress within the field can assist with escaping the circularities. Jamee Elder (2023) identifies that in gravitational wave testing, a context where there is similarly a threat of circularities, there is an iterative process of "improving the precision of measurements and further exploring dependency relationships". This is very similar to the improvements sought in cosmology. Further data on the dipole, especially as technology improves (§4.4.2), is expected to be enough to settle its nature independently (§3.3.2). The improvement of algorithms, ensuring that the simulation results are reliable and robust coupled with the reduction of systematic errors — an effort reported to be increasingly successful with each data release of the Planck mission — are also relevant aspects in improving measurements. Moreover, the number and quality of isotropy checks have been increasing with rising computation power, statistical understanding, and more accurate signals, enhancing the reliability of the results. In a similar vein, a better understanding of the foreground might result in the clear establishment of the CMB signal as blackbody (§3.3.3), escaping one more testing circularity. While not discussed as a part of this paper, dependency relationships are a part of CMB research, as well, for example, the interplay of initial conditions, inflation, and the statistical fluctuations in the CMB. All these, are ways that iterative epistemic progress can be achieved to assist with discerning the isotropy of the CMB and by extension testing a part of the cosmological principle.

Similar arguments can be applied to the effort of proving homogeneity independently. Improvements in data measurements, technologies, methodologies, the nature of astronomical objects and even the understanding of general relativity can potentially enable some of the idealised tests described in §3.5. Some tests, such as curvature tests, have been suggested to be feasible within the next few decades. Further precision in the data might allow for identifying the kinematic SZ effects more easily and allow for the homogeneity tests to be conducted. If that is not possible consistency tests of the cosmological principle can also be improved. By relying on different underlying assumptions and observables they might suggest through iterative constraining the precise domain and scale of the principle, if it is valid. There are many reasons, therefore, to be optimistic about the potential of testing the cosmological principle in the future, even if it is not possible now.

4.4.4 The Physical Status of the Cosmological Principle and the Cosmological Models

ΛCDM through the fitting procedures integrates independent frameworks within physics, using empirical guidance (de Baerdemaeker, 2020). Its role is not that of a foundational theory but of a descriptive enterprise, one that in some ways can still be predictive and even suggest new physics. Because of the nature of historical science models their physical status can be in doubt. Depending on one's flavour of scientific realism their reality can easily be denied. Most famously Ian Hacking (1989) has denied the realism of astronomical entities because of the way modelling and testing works in astronomy. Identifying the role of cosmological models as explanatory has allowed for diminishing concerns about averaging, fitting, and idealisations of observations. The issues described in §4.1 and in §4.2 reemerge in a standard reading of realism. If transitioning between scales is poorly understood, because of averaging, and by extension the validity of the model in those lower scales, one can question its reality. In regards to fitting, the quality of the fit creates questions on the physical status of discrepancies from the model. Lastly, idealising observations by simplifying the geometry raises concerns about the realism of the model in general.

More pragmatic approaches to realism either reject the possibility of a realism anti-realism debate or redefine realism. Currie (2018), in his defence of the historical sciences, rejects the debate and the main justification for it — historical inductions arguments — because they miss important aspects of science. For him, those aspects are context-sensitivity, pluralistic potential progress, and indirect gains from unexpected results and false theories that lead to the eventual accumulation of knowledge. On the other hand, Chang (2022), having identified features of science comparable to those of Currie, uses them to reconceptualise realism as a pragmatic endeavour, rooted in the practices of science. His activist realism is normative, focused on context-sensitive epistemic needs, and making iterative progress. Cosmology fits well with this understanding of realism, as its utilisation of different epistemic methods in order to achieve the goal of describing the universe happens primarily through the iterative progress described in §4.4.1.

Another way to defend cosmological models was offered by Christopher Smeenk (2020), though his outlook leaves their status ambiguous. Smeenk suggests adopting the understanding of scientific theories presented by Howard Stein (1995) in order to understand cosmology. The first aspect is giving a central role to the observer, by "schematising" them, as the mediator of observations and mathematical formulations. The second characteristic is that theories should be evaluated based on their fruitfulness and consistency within their empirical domain. Observers are important in cosmology because of the nature of the traces used in the discipline, as the context of observations plays a significant role in interpreting the data and showing that it conforms with the theory. The model-dependence of understood entities and the idealisation of light propagation can be seen as ignoring this important aspect that needs to be reintroduced, in order to understand the products of cosmology. Regarding the second aspect of Stein's understanding, empirical consistency of the cosmological models is a requirement, though fitting might cause some concerns, and in terms of fruitfulness, cosmology has led to potential new physics. Under this schema, Smeenk defends cosmological models but suggests that the physical status of cosmological models is not well-established because one cannot be certain if discrepancies from the model are fitting remnants, or whether they demand an explanation. Such an argument goes beyond the realism debate but it does create concerns about entities, such as dark matter, for most strands of scientific realism. Becoming a realist about dark matter is considered ill-advised both in Hacking's epistemological scepticism about the capabilities of astronomy but also in the semantic dimension of standard scientific realism, because of the abundance of available models, with a thin common core (Martens, 2021). If, thus, the existence of postulated entities such as dark energy and dark matter is successfully established, that would settle the physical status of the model.

The cosmological principle as a feature of the standard cosmological model is in a similarly dubious position. On a Lakatosian reading of the history of cosmology, one could say that the cosmological principle has been part of the hard core, serving as a foundational feature upon which the cosmological research program was constructed.[7] It was taken as a principle of nature, a description of the facts of the world. In reality, it has acted more like a guiding principle, according to the schema devised by Fischer (Forthcoming) for principles in physics. Throughout the years its definition has shifted from a perfect cosmological principle to a weakened spatial version, and finally to a statistical formulation (§2.1). It has guided research and has been the basis to formulate and eventually successfully establish a handful of different models, with the most dominant in the last decades being ΛCDM. The principle has assisted the field in achieving massive epistemic gains. From the case study of the cosmological principle, one can infer that guiding principles can have the same guiding role, as in general physics. In this case, the guidance pertains more to the explanatory virtues and the specific model features expected to play an important role in the model.

Progress in cosmology, however, partly requires ceasing to identify cosmological endeavours as uniquely tied to this singular principle. While the principle has been productive there remain strong limitations in characterising the models it produced as genuinely physical. Some cosmologists have already argued that cosmology can proceed without any principles and that the cosmological principle should be discarded.[8] Such a claim, however, remains controversial and while the principle might still be untestable, in the near future, it is remarkably successful. This is not an appeal to stop utilising the principle and deny the success of models based on it. Instead, it is a suggestion to allow for the proliferation of alternatives and the continuation of efforts to constrain and test the principle, in order to either reject the standard model or converge towards a belief that it is genuinely physical.

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[7] The hard core, in Lakatos' philosophy of science, consists of the irrefutable fundamental theses that define a research program.

[8] For example, famous cosmologist Alexei Starobisnky has argued this in a talk given at the conference "A discussion on the cosmological principle", at the Asia Pacific Center for Theoretical Physics, Pohang, South Korea, on the 25th of October 2022.

Such progress, as described throughout this section, would eventually lead to the cosmological principle becoming a principle of nature, or in the historical science terminology, one of the traces that need to be accounted for, potentially even a smoking gun.

Chapter 5

Conclusion

In cosmology, prima facie, there are several concerns about the epistemic status of the discipline's models. These concerns arise from the nature of available data and its associated practices, particularly when compared to the exemplary standard scientific practice of experimentation. There is a genuine threat of vicious circularities because of confirmation holism, which could make independently testing hypotheses about cosmological models impossible. In this thesis, I examined this issue through a key component of modern cosmology: the cosmological principle.

The cosmological principle has a long history within cosmology, making it an integral part of the modern standard cosmological model ΛCDM. The reliance of cosmologists on the principle invites scepticism as justifying it in an a priori way is unsatisfactory. Coupled with the fact that the principle was historically favoured because of aesthetics and its simplification of the Einstein equations, it raises questions about the principle's validity and how well it corresponds to the actual universe. This has led to the search for independent verification of the principle.

One approach to achieving this goal has been testing the principle through observations of the CMB. These tests, however, have potential circularities. The Planck collaboration has been the latest mission attempting to understand the CMB. One of their main objectives was to check whether the CMBR is statistically isotropic. In order to make the tests possible first the intensity signals are calibrated into temperature, with the help of the dipole, that is identified with the local motion of the Earth relative to the CMB rest frame. This creates a circularity because the fluctuation represented by the dipole is disregarded by being understood as solely caused by our local motion. Additionally, the CMB signal needs to be separated from the foreground contamination of other radio sources within the universe, prior to any isotropy checks. For this, the collaboration utilises four simulation algorithms with different methodologies and initial assumptions. Two of the algorithms assume isotropy and two that the CMB is a black body. This introduces another circularity because the black body nature of the CMB is an assumption of isotropy in disguise since black bodies are diffuse emitters. Thus, despite the consistency of results from the isotropy tests to the choice of component separation method, they might not be robust. If the dipole and the blackbody nature of the CMB, however, can be established independently, which appears to be a possibility in the future, then, the isotropy of the CMB can be inferred from the testing. Multiple isotropy checks by the collaboration generally agree with the statistical isotropy of the signal, though a few tensions exist. Interpreting these tensions presents another difficulty due to the look-elsewhere effect and the statistical nature of the fluctuations.

Homogeneity, unlike isotropy, cannot be directly tested using the CMB because the CMB is idealised as an event happening in a single time slice and can be observed only from one spacetime point. In overcoming this limitation, the generalisation of the EGS theorem has been instrumental. The EGS theorem proves that if all observers view an isotropic CMB, isotropic dark matter, and isotropic spatial expansion, then the metric for that spacetime is FLRW. One strategy for justifying the cosmological principle, using the theorem, is adopting the Copernican principle, since if all observations are representative of the larger class and we observe an isotropic CMB, then, other observers do, as well. This strategy is not necessarily satisfactory as it exchanges one principle for another, and adopting it with a probabilistic justification is not convincing. The EGS theorem has also inspired suggestions for possible tests that could showcase homogeneity. These tests rely on the kinematic SZ effect to view a reflection of the CMB from another observer's standpoint. Although these tests require idealisations that currently render them impossible without falling into circularities, they have been employed to constrain alternative cosmological models based on the LTB metric.

Beyond the CMB there are certain aspects of cosmology which amplify the the threat of circularities when attempting to conduct independent tests. Averaging observables in general relativity is non-trivial because of the nonlinear nature of the equations. It is essential, however, to understand the cosmological principle as valid on a certain scale and to transition between scales. Another issue is the fitting problem of matching an exact solution of the Einstein equations, through a model, to the real lumpy universe. An attempted solution here is perturbation theory, though it is difficult to ensure that observables remain consistent even if the perturbed metric is arbitrarily close to the FLRW one. Lastly, cosmologists idealise observations by assuming that the signals travelled through an FLRW geometry, creating another process where local effects can be ignored. These are all potentially problematic, but they are somewhat necessary because of the nature of the evidence and the underlying theory, namely general relativity.

In astronomy, and by extension cosmology, the reliance on traces or signals from our past light cone imposes significant methodological constraints. These amplify threats of confirmation holism within the historical sciences. Because, however, they rely on creating unified explanatory accounts over hypothesis falsification, the circularity concerns are less potent. This does not mean circularities should be ignored, but independent testing only plays a secondary role when crafting a unified account explaining the evolution of the universe. What matters more is this account being the best available explanation. This is reflected in how ΛCDM functions in modern cosmology, as tensions are not sufficient to falsify the model. Instead, they only prompt cosmologists to search for explanations that fit within the model. Idealising observations and fitting are also justified by the methodology of the historical sciences, as fitting is a way of constructing the best possible explanation from the available traces and idealisations can be treated similarly to all other circularities, making them less threatening. How models are constructed in cosmology also relates to the nature of traces and plays its own role in reducing some concerns. Cosmology seeks to model and understand the large-scale behaviour of the observable universe. Thus, transitioning between scales through averaging and fitting into an idealised geometry are more acceptable because the goal is primarily descriptive. The worry of these circularity threats, therefore, diminishes because of the nature of cosmological models and because of the methodology of the historical sciences, of which cosmology is one.

Even though cosmology has a weaker epistemic basis compared to the traditional experimental sciences, it can still make progress. By engaging in what Currie (2018) calls methodological omnivory — utilising every promising available method — cosmologists can maximise epistemic gains, in spite of the data constraints. This progress can be achieved through three different interrelated approaches. The main way is iteratively through a cycle of hypothesising, checking with the observable evidence, and further improving the model, similar to what Chang (2022) defends. Another approach is eliminatively by testing and ruling out alternative models as worse explanations, through testing or other epistemic virtues. Lastly, progress can occur in terms of fruitfulness primarily through the suggestion of new physics, stimulating research inside and outside the field. Innovations in technology, methodology, algorithms, and theoretical frameworks can all contribute to progress. This is evident in the development of our understanding of the CMB and the possible tests we can construct with the evidence it provides us. Despite the lesser impact testing circularities have on the accounts of cosmology, solving them is still a way to make progress. Independently establishing the cosmological principle would help the field progress significantly by eliminating several other categories of potential alternatives and increasing our trust in the current standard cosmological model and the new physics it suggests.

Therefore, there are several reasons to be, as Currie (2018) suggests, optimistic about the historical sciences. Cosmology can progress iteratively regardless of circularities and it can potentially solve the circularities currently present in the testing of the cosmological principle, in the future. The nature of the methodology and cosmological models can make it difficult to ascertain the physical status of the entities within the model, especially from a traditional scientific realist perspective. From a pragmatist reading in the spirit of Chang (2022), however, cosmology is very successful according to its aims, methods, and results which are rooted in the context of practice and include the limitations of the discipline. While through the pragmatist lens, the use of the cosmological principle can be justified, its status remains ambiguous. It has served as a guiding principle determining where inquiry should be focusing in cosmology while being thought of as a principle of nature. Establishing it, however, as a principle of nature or rejecting it through independent testing, will be an important step in cosmology and it increasingly appears that it might be possible. Until then it is important to allow for the proliferation of alternatives and continue to test the consistency of the cosmological principle and further constrain it.

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